A set of optical techniques for studying the dynamics of a discharge in millimeter-length intervals: the development of a spark discharge in air in the pin-to-plate geometry

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Abstract. Techniques are described and some results of experimental studies of a spark discharge in the tip-plane geometry in air at atmospheric pressure are presented. It is shown that, at the initial stage (a few nanoseconds after breakdown), the microstructure of the discharge is formed in the form of a set of a large number of microchannels. It was found that by the moment of time 20 ns the spark channel acquires a single cylindrical boundary, the electron concentration at this moment reaches a maximum value of $2 \times 10^{19} \text{cm}^{-3}$, after which an intense expansion of the channel begins, and from 60 ns a shock wave leaves its boundary.

1. Introduction

Spark discharge research is of great practical interest. On the one hand, such a discharge is a negative factor, causing short circuits and damage to structural elements in various high-voltage devices. On the other hand, it finds applications in various fields such as surface treatment, plasma aerodynamics, fuel combustion initiation, etc. [1-8].

Some of the first detailed studies of the spark discharge were carried out more than half a century ago [9-10]. In these works, the stage of radial expansion of the spark was studied at times of more than 100 ns after breakdown with the formation of a shock wave, and the existence of a highly conductive plasma channel separated from the wave by an intermediate shell was discovered. On the basis of the data obtained, a physical and mathematical model was proposed that allows one to describe the position of the boundaries of a cylindrical shock wave and a conducting region in relation to time.

Subsequent development of experimental research technologies, including methods of laser sensing with nanosecond and subnanosecond time resolution, provided new data on the dynamics of a spark discharge, including its initial phase [11-16,17]. Thus, it was found that the concentration of electrons in the channel at times $\leq 10$ ns can exceed $3 \times 10^{19} \text{cm}^{-3}$ [12-16,17], and the electron temperature at times of 10-20 ns after the voltage is applied can reach values $T_e = 5-6 \text{eV}$ [11]. The use of the technique of shadow photography and the interference technique of high spatial resolution (units of micrometers) made it possible relatively recently to register the microchannel (filamented) structure of the spark channel [13-16, 18]. It was found that the discharge channel is not continuous, but is a collection of many microchannels (a few tens of microns in diameter). The microstructure forms at times less than 10 ns after breakdown. In addition to the spark, the microstructure was also recorded in diffuse and barrier discharges in air at atmospheric pressure [14, 19]. It should be noted that for the first time the microstructure of discharges in air was recorded by the autograph method in works [20-22].

Since the development of spark and other types of discharges with an internal microstructure has not previously been considered in the classical theory of a gas discharge [18], it is highly relevant to
obtain new experimental data on such discharges and develop the corresponding physical and mathematical models for their description.

2. Research methods and analysis of the results

This paper presents the methods and some results of experimental studies of the development of a spark discharge in air at atmospheric pressure in the tip (anode)-plane geometry.

The discharge was investigated on a stand including a voltage pulse generator (GVP), a cable line, a discharge gap, diagnostic equipment, and a synchronization system (figure 1). The equipment and techniques are described in detail in [13, 14, 24-25, 18].

Generation of voltage pulses was provided by switching the charged capacitance to the cable line. The voltage amplitude at the output of the GVP was 30 kV and had a positive polarity. The rise time of the voltage pulse at a level of 0.1–0.9 was 7 ns.

The cable line 7 m long was loaded onto the tip-plane discharge gap. An axisymmetric stainless steel electrode with a length of 40 mm, a diameter of 10 mm, an apex angle of 14°, and a radius of curvature of 0.1 mm was used as a tip. The flat electrode is made of aluminum alloy; its working part is similar in shape to a spherical segment 4.5 cm in diameter and 1.5 cm thick. The interelectrode gap was 1.5 mm.

The timing and amplitude characteristics of the signals were recorded using an oscilloscope with a bandwidth of 500 MHz and a digitization rate of 2 Gs/s. The voltage (capacitive divider) and current (resistive shunt) were measured at the output of the GVP. The time resolution of the divider and the shunt is no worse than 1 ns.

The optical registration system implemented within the framework of the stand made it possible to obtain shadow images, interferograms and frames of high-speed photographic registration of various stages of the discharge [13, 14, 18, 19]. The system included a source of probing radiation - a laser (wavelength \( \lambda \)=532 nm, pulse width at half maximum 6 ns), lens, light filters and digital electro-optical camera. A plane-parallel laser beam, passing through the discharge region perpendicular to the axis of the electrode-tip, was recorded by an electron-optical camera. In the region where the discharge was formed, the transverse size of the laser beam was approximately 1 cm and had a Gaussian profile. The registration system provided a spatial resolution of no worse than 5 µm.

Using the described registration system and an optical scheme based on a Mach-Zehnder interferometer, an interference technique was implemented [18].

The exposure of frames of shadowgrams and interferograms was determined by the duration of the laser pulse.

In experiments on photographing the self-glow of the discharge, the laser was not used. The frame exposure of the electro-optical recorder was 40 ns. When photographing the early stages of the discharge (at times less than 40 ns), part of the exposure time was ahead of the beginning of the discharge formation.

Visualization of various stages of the discharge process was provided by shifting the moment of starting the optical registration system relative to the moment of breakdown. The shooting was carried out in one-frame mode - one frame per pulse.

The measurement of the electron concentration was carried out according to the known dependence of the refractive index of the medium \( n \) on the electron concentration \( n_e \). In the high frequency limit, when the laser frequency \( \omega = \frac{2\pi c}{\lambda} \approx 3.5 \times 10^{15} \text{s}^{-1} \) is much higher than the frequency of elastic collisions of electrons with heavy particles \( (\omega >> \nu_m) \) and plasma frequency \( (\omega >> \omega_p) \) the refractive index can be written as follows [17] \( n \approx \sqrt{\varepsilon} \approx 1 - \frac{1}{2} \left( \frac{\omega_p}{\omega} \right)^2 \), where \( \varepsilon = 1 - \left( \frac{\omega_p}{\omega} \right)^2 \) - dielectric constant of plasma. For convenience, the following expression is used [23]:
Accordingly, the phase shift acquired by the wave when passing through the discharge region is
\[ \Delta \varphi = \Delta k \cdot \lambda = \Delta n \cdot L, \]
where \( \Delta n \) – average change in refractive index along optical inhomogeneity, \( L \) – optical inhomogeneity width. Taking into account (1), we obtain the following expression for determining the average concentration of electrons \( n_e \) in the bit channel:

\[ n_e \cdot L = \frac{\Delta k}{4.46 \cdot 10^{14} \lambda}. \]

Here \( \Delta k \) – the amount of offset fringes expressed in fractions of the bandwidth. The determination error \( n_e \) was no more than 20%.

After the breakdown of the gap in the discharge circuit, an oscillatory process with an exponential decay of current and voltage occurred. The oscillation period was 1 \( \mu \)s, the current amplitude and its decay time were, respectively, 1.5 kA and 2 \( \mu \)s. In this case, two characteristic moments of time were distinguished on the oscillograms: the appearance of a voltage across the discharge gap and a breakdown. The average delay between them is 4 ns. The moment of the breakdown was taken as the moment when the current began to rise and, accordingly, the voltage dropped.

Figure 2 shows examples of interferograms of a discharge at different times after breakdown, on the basis of which the values of \( n_e \) are determined. It should be noted that, as the discharge develops, the displacement of the interference fringes is initially recorded near the cathode and anode surfaces, and then in the rest of the region. This circumstance indicates that a sharp increase in \( n_e \) first occurs in the near-electrode regions. This is also confirmed by the regions of bright glow of the initial stage in figure. 3. This means that processes on the electrode surface can play an important role in the formation of a highly conductive channel.

By the time 2 ns after the breakdown, a single channel with a radius \( R = 150 \mu m \), consisting of many microchannels with (~100) a radius \( r = 5 \mu m \). Over time, the microchannels increase in diameter. Until the moment of time 20 ns, the channel diameter practically does not change, at this time the channel acquires a single continuous boundary in shape close to cylindrical, and the electron concentration in the central region of the discharge gap reaches its maximum value \( 2 \cdot 10^{19} \text{cm}^{-3} \). Then, radial expansion of the channel begins with a speed of \( \sim 5 \text{ km/s} \), during which the expansion rate and electron concentration decrease [25, 27]. By the time 60 ns, a shock wave begins to move away from the conducting channel.

Based on consideration of the kinetics of plasma-chemical processes in the range of 20-60 ns and explosive phenomena on the cathode surface, it was found that the electron temperature after the...
formation of a single channel boundary is at the level \( T_e = 2-3 \text{ eV} \), and the gas temperature is close to the value \( T_g \sim 1 \text{ eV} \) [24-27].

**Figure 2.** Discharge interferograms at different time instants relative to the breakdown instant: \( a - 2 \) ns, \( b - 5 \) ns, \( c - 8 \) ns, \( d - 30 \) ns. The tip electrode is on top. The red rectangles in figures \( b \) and \( c \) denote fringe shift regions.

**Figure 3.** Photo of the discharge glow 2 ns after the onset of breakdown. The tip electrode is on top.

Under these conditions, the frequency of electron-electron interaction is about \( \nu_{ee} \sim \frac{3.7 n_e \ln \Lambda}{(T_e[K])^{3/2}} \sim 10^{14} \text{ s}^{-1} \) [17], where \( \ln \Lambda = 7.45 + \frac{3}{2} \ln(T_e[K]) - \frac{1}{2} n_e[\text{cm}^{-3}] \) — the Coulomb logarithm.

The time of dissociation and ionization can be estimated as \( \tau_{dis} \sim \frac{1}{k_{dis} n_e} \) and \( \tau_{ion} \sim \frac{1}{k_{ion} n_e} \) where \( k_{dis} \), \( k_{ion} \) are ionization and dissociation constants [25]. For the dissociation of oxygen and nitrogen molecules, we obtain \( \tau_{dis} \sim 10^{-12} \text{ s} \). For the ionization of atoms O and N, we obtain \( \tau_{ion} \sim 10^{-9} \text{ s} \). Thus, inelastic collision frequencies are \( \nu_{dis} \sim \frac{1}{\tau_{dis}} \sim 10^{12} \text{ s}^{-1} \) and \( \nu_{ion} \sim \frac{1}{\tau_{ion}} \sim 10^{9} \text{ s}^{-1} \) respectively. It should be noted that inelastic collision frequency is much less than the frequency of electron-electron collisions \( \nu_{ion} \ll \nu_{dis} \ll \nu_{ee} \).
Debye radius is \( r_D = \left( \frac{\varepsilon_0 k}{n_e e^2 \left( \frac{1}{T_e} + \frac{1}{T_i} \right)} \right)^{1/2} \sim 1 \) nm, where \( k, e, \varepsilon_0 \) – Boltzmann’s constant, electron charge and dielectric constant. In this way \( r_D \) is significantly smaller than the spatial scale of the problem \( r_D \ll R \). This circumstance makes it possible to consider a quasineutral plasma with a Maxwellian electron energy distribution function, which, in accordance with the Spitzer formula, gives the conductivity value \( \sigma = 1.53 \cdot 10^{-4} \left( \frac{T(K)}{\ln \Lambda} \right)^{3/2} \sim 200 \ \Omega^{-1} \cdot \text{cm}^{-1} \).

Let us show the applicability of formula (1). Due to the great importance \( n_e \), electron elastic collision frequency \( \nu_m \) is determined by scattering on ions. Accordingly, we obtain the following estimate \( \nu_m \sim \nu_{ee} \sim 10^{14} \ \text{s}^{-1} \). Plasma frequency is \( \omega_p = \left( \frac{n_e e^2}{\varepsilon_0 m_e} \right)^{1/2} \approx 1.8 \cdot 10^{14} \ \text{s}^{-1} \), where \( m_e \) – electron mass. Thus, we have the following relation \( \nu_m \sim \omega_p \ll \omega \), which gives grounds to use expression (1) to find the electron concentration in the plasma channel.

3. Conclusions
A description of a set of techniques, including high-speed and shadow photography, as well as an interference technique, with nanosecond time and micrometer spatial resolutions, for studying discharges in intervals of millimeter lengths, are presented. Using these techniques, it was found that during the development of a spark discharge in air at atmospheric pressure in the tip-plane gaps, a few nanoseconds after breakdown, the channel is a combination of a large number of microchannels. Then, by the time 20 ns, the spark channel acquires a single continuous boundary, and the electron concentration at the center of the discharge gap reaches its maximum value \( 2 \cdot 10^{19} \ \text{cm}^{-3} \). At this time, the temperature of electrons and gas are, respectively, \( T_e \sim 2-3 \ \text{eV} \) and \( T_i \sim 1 \ \text{eV} \), and the channel conductivity is about \( \sigma \sim 200 \ \Omega^{-1} \cdot \text{cm}^{-1} \). Then, the radial expansion of the channel begins with a speed of \( \sim 5 \ \text{km} / \text{s} \), during which the expansion rate and the electron concentration decrease, and by the time 60 ns a shock wave begins to move away from the spark channel.

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