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Formation of waves in explosive processes on a cathode with
and without an external magnetic field

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Abstract. The explosive model for the development of a cathode spot involves the release of
high energy in the emission center, followed by heating and explosion of the micro-tip. The
specific energy emitted during a very short time \((\leq 10^8 \text{ s})\) is \(6 \cdot 10^7 \text{ J/kg}\). The formation of the
cathode spot coincides with the onset of a sharp increase in current and a decrease in the
voltage across the discharge gap as a function of time. The near-cathode plasma spectrum is
characterized by intense lines for the Al II cathode material with high excitation potentials and
an intense continuum in the 260–360 nm range.

1. Introduction

The first stage is observed when a cathode spot is forming, including the heating of the metal in the
solid state, melting, and heating of the liquid metal prior to the beginning of evaporation. The second
stage is the explosion stage, which is accompanied by a sharp increase in the resistance of the
conductor and a decrease in the density of the conductor. If the first stage can be characterized only by
one thermodynamic variable, the temperature or specific energy, the second stage is associated with
the drift of the electron beam through the plasma of a volumetric glow discharge with a significant
energy release and an increase in temperature [1–3].

The mechanisms of cathode spot formation and the thermionic electron beam as well as the spark
channel and arc stage in molecular and inert gases practically coincide. In the breakdown of molecular
gases, as a result of the overlapping plasma streamer of the gap, ionization fronts also propagate to the
anode as a result of thermionic beam drift. Unlike molecular gases in inert gases, the formation of a
cathode spot corresponds to the voltage step on the current-voltage characteristic. With the formation
of the cathode spot, a drift in the thermionic beam is observed, leading to a sharp increase in the
conductivity and specific energy input. The drift of the electron beam leads to the formation of a spark
channel with \(d = 0.1 \text{ mm}\) [1, 2].

Due to the drift of the electron beam with \(eU = 5 \text{ keV}\), the streamer channel is transformed into a
spark channel. The drift velocity and the duration of the electron beam are determined by the relations

\[
\frac{mv^2}{2} = eU; \quad v_n = \left(\frac{2eU}{m_e}\right)^{\frac{1}{2}} \approx 10^7 \text{ m/s}
\]

\[
\frac{m}{dt} = eE; \quad \int_0^v dt = \int_0^{v_n} \frac{m_e}{eE} dv; \quad t_n = \frac{m_e}{eE} v_n \approx 10^{-11} \text{ s}.
\]

Single-shot shooting of a single spark channel with the help of an electron-optical converter Ar
breakdown in short intervals in homogeneously pulsed electric and magnetic fields makes it possible
to trace the development of the streamer because the time of its formation, which occurs mainly at the
anode, occurs at an electron density of ~10^{12} \text{ cm}^{-3}. The plasma streamer continuously propagates at insignificant overvoltages, and at large overvoltages, it pulses to the cathode at a speed of ~3 \cdot 10^{8} \text{ cm/s} [3, 4], forming a high-pressure glow volume discharge with an electron density of ~10^{14}–10^{16} \text{ cm}^{-3} [2]. As the plasma streamer approaches the cathode, the electric field strength sharply increases to E \sim 10^{8} \text{ V/m}, which leads to the formation of a cathode spot with the onset of a sharp increase in current with an increase in its density. The concentration of electrons in the thermocouple is determined from the relation
\[ n_e \sim \frac{j}{ev} \sim 10^{12} \text{ cm}^{-3}. \] (3)

2. Results

With the formation of a cathode spot, the electron density sharply increases, which leads to an increase in the current density and a transition of the volume discharge to the spark channel [2, 3].

As a result of the electron beam drift in a nonisothermal plasma, depending on the ratio of the electron drift velocity, \( v \), and the thermal velocity of electrons and \( v_{Te}, v_{Ti} \), ion-sound or ion-sound instabilities can be excited together with Buneman [5, 6].

According to our experiment, \( E \sim 10^{4} \text{ V/cm}, v_{Te} \sim 10^{12} \text{ c}^{-1}, T_i \sim 10^{3} \text{ K} \) and \( v \sim 10^{7} \text{ cm/s} \), which is much larger than \( v_{Ti} \sim 10^{5} \text{ cm/s} \). Thus, under the conditions of our experiment, the ion-acoustic instability criterion was realized.

Ionic-acoustic instability (turbulent plasma heating) develops before thermodynamic equilibrium in the plasma occurs \( (T_i \approx T_e) \). The instability increment is proportional to the current velocity, which caused the experimentally observed decrease in the time with a sharp drop in voltage [3].

The further stage of the discharge is characterized by an isothermal plasma with constant conductivity (the stage of a spark channel and the burning of a quasi-stationary arc).

Thus, the spark breakdown of gases proceeds due to the formation of the following stages: avalanche-streamer, volumetric glow discharge, cathode spot, electron beam drift, turbulent plasma heating, a spark channel with highly ionized plasma, a burning quasistationary arc and plasma decay.

Let us consider the dependence of the power released at all stages of Ar breakdown on the magnetic field strength [7]. The volt-ampere characteristics of the breakdown were constructed for different external longitudinal magnetic field strengths during which the energy deposition in the discharge gap was determined. The experiment was conducted under the following conditions: \( p = 2280 \text{ Torr}; U_{alt} = 7 \text{ kV}; C = 1 \mu \text{F}; W = 55\%; d = 0.003 \text{ m}. \)

The maximum energy input occurred at the onset of a sharp decrease in voltage (the formation of a narrow channel and its expansion) during the time interval of 300–450 ns from the leading edge of the voltage pulse that was applied to the gap.

With the formation of a cathode spot and a spark channel, the intensity of the luminescence of the argon ion lines increased, and there was a simultaneous intense continuous spectrum recorded in the region of 350–360 nm. This corresponds to the radiation of a plasma of a completely ionized plasma channel with a diameter of \( 2r = d = 0.1 \text{ mm} \). At the channel-arc stage, the degree of ionization reached 100\%, and the temperature is determined from the conductivity, \( \sigma \approx 10^{-3} \text{ T}^{3/2} \text{ m}^{3/2} \text{ cm}^{-1} \).

The time for a sharp decrease in the breakdown voltage with the formation of a cathode spot decrease in a magnetic field. This indicates the acceleration of the propagation process of a monoenergetic electron beam from the cathode to the anode (i.e., the formation of a spark channel) and the transition to the stage of a quasi-stationary arc. The external longitudinal magnetic field also prevents the expansion of the spark channel, which indicates the commensurability of the magnetic pressure with the kinetic
\[ \frac{\mu_0 H^2}{2n} \approx nkT, \] (5)

\[ T \approx \frac{\mu_0 H^2}{2nk} \sim 10^6 – 10^7, \text{K}. \]
3. Analysis of the results
According to the streamer mechanism of high-pressure gas breakdown with the formation of a cathode spot, a mono-energetic electron beam forms, which initiates the formation of a highly ionized plasma spark channel. Meanwhile, there is a decrease in voltage across the gap when it is closed by a germinating plasma channel.

In the case of molecular gases, the single-channel transformation model is also valid, assuming an increase in the conductivity of the streamer plasma, which is characterized by a uniform luminescence intensity. The formation of a spark channel sharply increases energy release, which leads to an explosive expansion of this area.

The electric field of the cathode layer, \( E_k \sim 10^8 \text{ V/m} \), in the presence of micro-inhomogeneities and dielectric impregnations is sufficient to initiate explosive emission and to form a cathode spot.

The avalanche of electrons in the transition from auto to the explosive-emission regime is called an "ecton". The number of electrons in the ecton is \( \sim 10^{10} \sim 10^{11} \) [5]. In this case, an electron shock wave is initiated from the micro-emitter at a speed of \( \sim \sqrt{e/m} \) (\( e \) is electron energy, \( m \) is electron mass). It forms a spark channel and an anode spot in the discharge area. Electrons from the cathode surface in the transition from the field-emission to the explosive-emission regime get into the area of the strong field and enter a regime of continuous acceleration. The critical field, at the excess of which electrons enter the regime of continuous acceleration, is [6, 7]

\[
E_{cr} = 3.38 \cdot 10^3 p z^*/I
\]  

(7)

where \( z^* \) is the number of electrons in the atom, and \( I \) is the average excitation energy or the average energy of inelastic losses. For argon, \( z^* = 18, I = 100 \text{ eV} \) and \( E_{cr} = 600 \text{ V/cm\cdotTorr} \).

The generated shock wave has a velocity of \( \sim 10^7 \text{ m/s} \) at an electron energy of 10 keV [8].

The decrease in the intensity of the spectral lines for ions and the increase in the intensity of the continuum after 30 ns indicates an increase in the plasma temperature in the spark channel at the early stages of its formation.

4. Conclusions
We showed that under electric energy inputs in magnetic fields, the radiation of the visible spectral region from the channel is absorbed at the front of the shock wave. The magnetic field contributes to the development of the shock wave front and its faster degeneration into the sound wave.

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