VACUUM PULSE BREAKDOWN IGNITION IN A GAP WITH HIGH-CURRENT-DENSITY CATHODE

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ABSTRACT

This article deals with the experimental results of the research on specific features of prebreakdown states origins and conditions of high-vacuum breakdown development of the inter-electrode gap, in particular when the cathode is a high emission material, which allows you to have the density of thermionic emission current up to several hundred amperes per square centimeter. It is shown that in the presence of thermionic current values of the current density up to 80 A/cm^2 pre-breakdown states take place on the leading edge of the pulse, and then on the trailing edge and pulse plateau. Pre-breakdown state on pulse plateau subsequently develop in the breakdown of the electrode gap. When increasing current density up to 440 A/cm^2 and above, high-voltage the breakdowns through microsecond intervals occur. An empirical relationship between the breakdown voltage and the current density for different values of the inter-electrode gap is established. Breakdowns lead to significant erosion of the cathode surface (craters formation).

1. INTRODUCTION

Thermionic cathodes are becoming widely used in contemporary vacuum electronics, allowing to obtain the current density of 100 A/cm^2 and higher in a pulsed mode [1].

However, when using high emission cathode materials, vacuum breakdowns of the electrode gap in pulsed mode take place. These vacuum pulse breakdowns not only prohibit the use of such emitters effectively (for instance, in microwave frequency devices), but also lead to sputtering and erosion cathode material. For example, commonly used lanthanum hexaboride emitter in the hollow cathode of the electric propulsion erosion strongly reduces the service life of the emitter and the electric propulsion as a whole [2].

The list of high emissive cathode materials includes emitters based on barium scandate and hafnate. The sintered thermionic cathodes composition of $Ba_xSr_{1-x}HfO_3$ and microfine tungsten (particle size less than 1 μm) makes it possible to obtain current densities up to 1000 A/cm^2 at the temperature $1600 - 1700$ K [3].

The aim of this work is to analyze the peculiarities of high-vacuum pulsed breakdown ignition of the inter-electrode gap in the case when the cathode in the cathode preheating unit is heated up to the temperatures when it can emit electrons with variable value of current density from 0 to 1000 A/cm^2.

2. EXPERIMENTAL

The sintered composite material $Ba_{0.75}Sr_{0.25}HfO_3$ with 20 % W (by mass) was selected as cathode material in our case. Experiments were carried out for a system with planar geometry. Cathode surface area was 3 mm^2. The anode was made of molybdenum in the form of a disk with a diameter of 10 mm and 2 mm thick. The distance between the cathode and the anode may have varied from 1.0 to 1.5 mm. Research was carried out with residual gas pressure of $10^{-4} - 10^{-5}$ Pa. Single pulses with amplitude voltage up to 6 kV were applied between the cathode and anode. Pulse shape was trapezoidal with a duration of 10 μs. The leading edge of the pulse had a duration of $1.0 - 1.2$ μs, and the trailing edge is $2.5 - 3.0$ μs.

Simultaneous recording of high voltage pulses and the current between the cathode and the anode was conducted during the experiment by using a multichannel digital oscilloscope RIGOL DS-1204B.

3. RESULTS AND DISCUSSION

The investigations of pre-breakdown states and pulse breakdowns directly were performed with gradually increasing temperature of the cathode and, hence, with increasing the density of the thermionic current.

At the beginning of the analysis at relatively low current densities ($10 - 11$ A/cm^2 at the cathode temperature 1530 K) current instabilities are beginning to show up at the leading edge of the pulse (Fig. 1), becoming evident through current fluctuations in the inter-electrode gap.

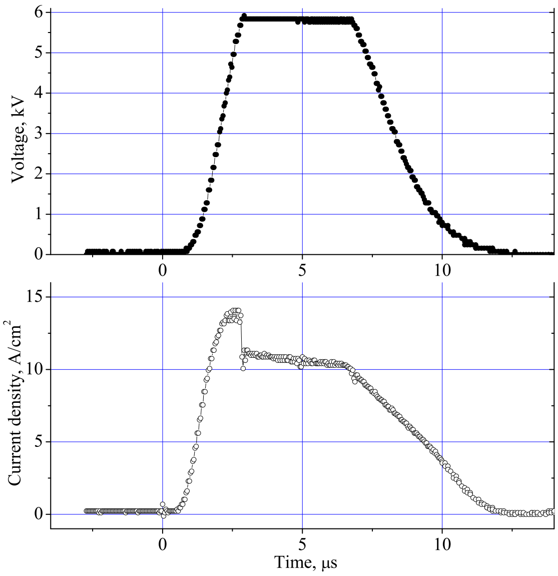

Fig. 1: Current instabilities on the leading edge of the pulse

Heating of the cathode at the above-mentioned constant temperature for about 1 h results in a decrease in those oscillations in the current. Consequently, a well-degassed and fully activated emitter possesses a rather small current instability on the leading edge of the pulse. A further increase of the cathode temperature, leading to an increase in current to values about 20 A/cm^2, causes only minor growth of instability on the leading edge, which does not result in the development of an inter-electrode gap breakdown.

Thus, the processes occurring at the cathode (field and thermionic emission) are followed by some increase in ionizing amplification of the primary electron current and minor short-term instability of the anode current.

By increasing the cathode temperature to 1550 K, and consequently growth of current density up to $60 - 62$ A/cm^2, the instability is beginning to show up on the trailing edge of the pulse (Fig. 2), i.e. initiating of the pre-breakdown condition.

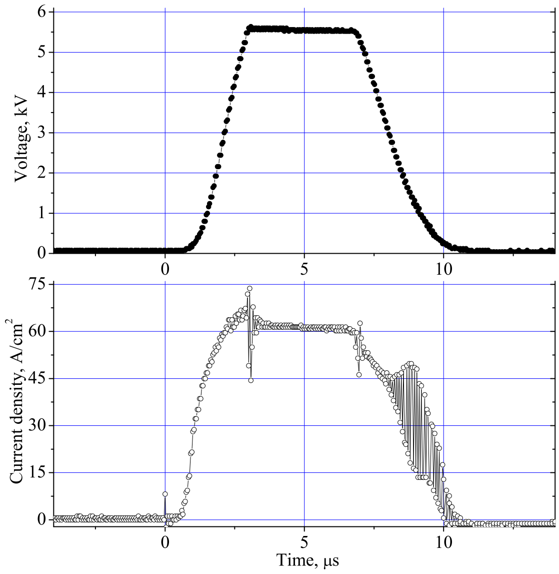

Fig. 2: Pre-breakdown states formed on the trailing edge of the pulse

The appearance of such pre-breakdown state is determined by several factors. It should be taken into account that barium and strontium cathode components are constantly evaporate from the heated cathode surface and deposit on the anode. Thus, the gravimetrically measured cathode component evaporation rate at 1700 K is $(6\pm2)\cdot10^{-7}$ kg/(m$^2\cdot$s), which corresponds to sublimation rate of $0.4 - 0.5$ μm/h. The presence of Ba and Sr on a molybdenum anode is confirmed by X-ray energy-dispersion microanalysis. Electrons accelerated in the inter-electrode gap, bombard the anode, heat it and cause thermal desorption and ionization of atoms of barium, strontium as well as spattering molybdenum atoms. As a result of these processes, a plasma-forming substance in the amount sufficient for formation of breakdown is found in the gap. On the plateau of the voltage pulse, the electron energy is approximately 5.5 kV. For such energies the ionization cross-section of Ba and Sr atoms is not high enough to cause avalanche. However, on the trailing edge of the pulse the electron's energy is reduced and therefore the probability of ionization by electron collision with the atoms of Ba and Sr increases. This situation is followed by appearance and development of instabilities on the trailing edge of the current pulse. The continued decrease in electron energy and in the density of thermionic current on the pulse decline leads to the disintegration of the pre-breakdown states in the gap.

A small increase in the electron current density (up to 80 A/cm^2) and a decrease in the applied voltage (up to 4 kV) results in the fact that the pre-breakdown states are beginning to form on the high-voltage pulse plateau. These states gradually progress and subsequently breakdown of the inter-electrode gap occurs (Fig. 3).

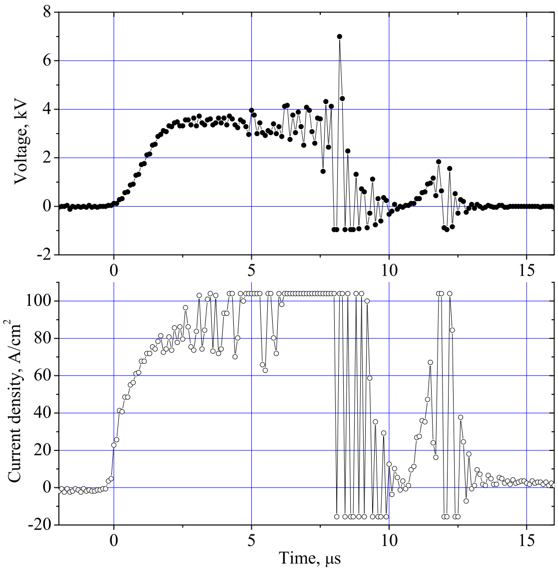

Fig. 3: High-voltage breakdown ignition

A further increase in the cathode electron (thermionic) current density up to 440 A/cm^2 is the cause that formation of pre-breakdown states occurs in small time intervals (about 1 μs) during the rise of the anode voltage, i.e. on the leading edge of the pulse, and a high-voltage pulse breakdown is ignited (see Fig. 4).

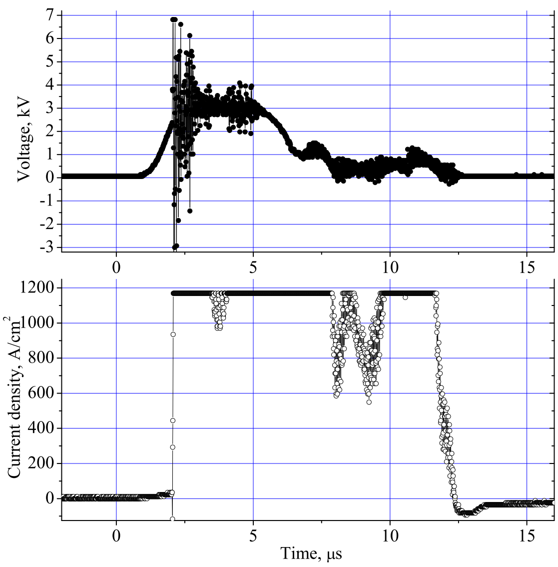

Fig. 4: High-voltage vacuum arc ignition

In cases when the thermionic current density exceeds to 440 A/cm^2, the sharp drop of the pulse voltage amplitude starts (see Fig. 4) in 4 μs from the beginning of the plateau. This drop of the anode voltage takes place at the expense of the limited source power during breakdowns.

It should be noted that the above patterns of pre-breakdown states and breakdowns of the inter-electrode gap for cathodes based on barium-strontium hafnates with tungsten are also typical for other cathode materials. For example, we also observed high pulse sparks and breakdowns in a single crystal cerium hexaboride cathode.

Since the concentration of ions and atoms evaporated from the anode surface is proportional to the power density applied to the anode, and the electron density in the inter-electrode gap is proportional to the emission current density, the speed of electrons near the anode is proportional to square root of applied voltage, it would be reasonable to expect a particular functional dependence of the breakdown voltage U_{br} on the primary (thermionic) current density j.

In order to prove this assumption, the experimental data on the breakdowns are shown in (Fig. 5) on a double logarithmic scale. These results indicate the presence of the expected correlation and make it possible to present it in the following form:

$$U_{br} = \alpha j^{-1/3},$$

where α is the coefficient which takes into account the gap's geometry and the anode's material. This figure indicates that breakdown voltage depends on the current density through the cathode-anode gap for two different values of the inter-electrode gap: 1.5 and 1.0 mm.

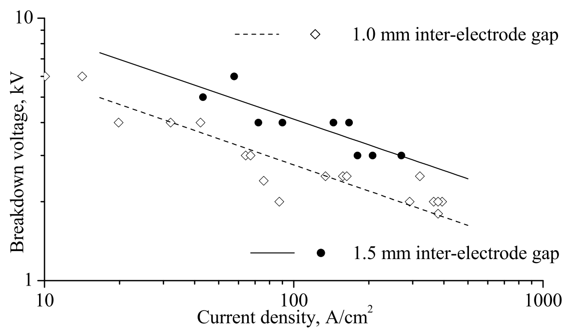

Fig. 5: Breakdown voltage vs. thermionic emission current for 1.0 *and* 1.5 *mm gap:* ● *and* ◇ *are experimental data;* — *and* - - - *are approximations*

In the case when the anode is a tantalum foil (0.1 mm thick) the breakdown started at approximately 6.0 kV on the pulse plateau even when the primary (thermionic) cathode current density was $5 - 5.5$ A/cm^2 (see Fig. 6). Such experimental data suggests that in case of a thin (not bulk) anode its heating to temperature at which the intensive desorption of evaporation products of cathode emission-active material begin to take less time than in the case of a massive molybdenum anode. In this case, the concentration of ions and neutrals is much higher.

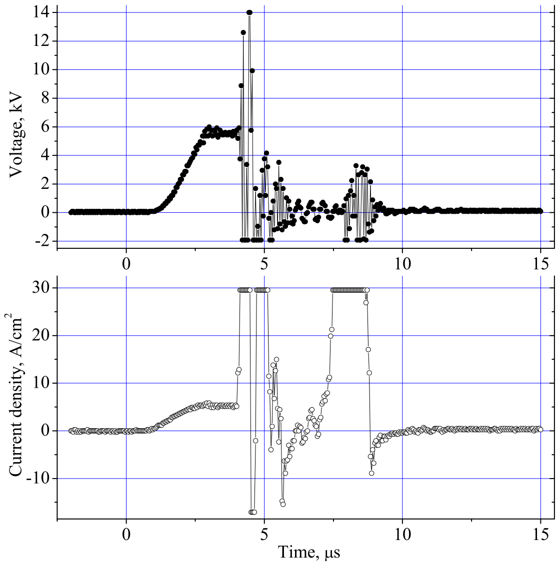

Fig. 6: The transition from the electronic emission current to the high arc for tantalum foil anode

After a series of experiments in which high pulsed breakdowns of the inter-electrode gap were recorded, a very large amount of erosion craters (Fig. 7) of various sizes were detected on the surface of the composite cathode material $Ba_{0.75}Sr_{0.25}HfO_3$ with 20% W (by mass).

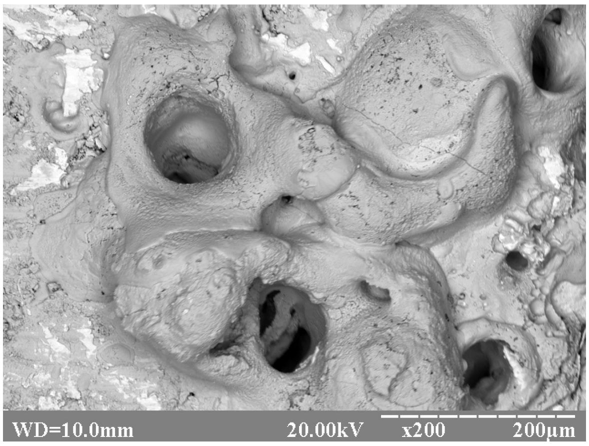

Fig. 7: SEM image of the cathode after high voltage vacuum breakdown

Additional heating of the near-surface layers directly by the emission current itself may also facilitate the appearance of such thermionic cathode erosion. This current goes through the layers of barium strontium hafnate with sufficiently high electrical resistivity. The above-mentioned overheating may lead to appearance of so-called current channels, in which a large-scale release of thermal power takes place.

4. CONCLUSION

Thus, carried out experiments allowed us to determine some peculiarities of pre-breakdown states initiation and breakdowns of the inter-electrode gap in the case when the cathode is a heated composite cathode material, which emits electrons with thermionic current density up to 440 A/cm^2 or even higher.

Pre-breakdown states are formed when the density of the thermionic current increases at first on the leading edge of the pulse, and then on the trailing edge and pulse plateau. After the thermionic current density reaches value of 440 A/cm^2, in case of the anode voltage growth, in approximately 1 μs high-voltage breakdowns take place.

The breakdowns of the electrode gap lead to a substantial erosion of the cathode material (appearance of craters).

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