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Fast particles and metal vapors from electrodes with small radii of curvature during nanosecond discharges in gases

In gaps with a non-uniform electric field, the high electric fields (>1 MV/cm) are achieved with a short voltage pulse front, which are enhanced by the accumulation of positive ions at the cathode and the formation of plasma. Based on the known experimental and theoretical studies of vacuum discharge, we hypothesized that the mechanism of destructive mechanical stresses in the surface layer of electrodes should also take place during nanosecond breakdown in gases. In this paper, the radiation of diffuse discharge plasma formed between two electrodes with a small radius of curvature was investigated when the discharge gaps were filled with air, nitrogen, argon, and helium at atmospheric pressure. With a nanosecond voltage pulse duration and energy inputs into the gas of <1 mJ/cm3, the tracks of particles emitted from bright spots on the electrodes, including those at a right angle to their surface, were recorded. It is shown that the length of the tracks depends on the polarity of the electrode and that at low energy inputs in the air the tracks end with a brighter glow region. It is established that the greatest radiation intensity during discharges in four different gases (air, nitrogen, argon and helium) are found in tracks that are formed in the air. From this result, as well as from the recorded duration of track glow pulses in hundreds of microseconds, it follows that the increase in the brightness of the radiation of the ends of the tracks during propagation in the air is determined by the heating of the electrode material during the interaction of the emitted particles with oxygen.

Keywords: tip-to-tip gap, nanosecond pulses, diffuse discharge, particle tracks.

Introduction

It is known that erosion of the electrode surface occurs during the formation of bright spots on the electrodes due to explosive emission of electrons as a result of breakdown processes [1]. The formation of craters on the cathode surface in vacuum and gas-filled gaps has been recorded in many studies, see, for example [1–3] and references in these publications. During nanosecond discharges in gaps filled with various gases, damage on the cathode surface, including crater-shaped damage, in the region of bright spots before a spark channel formation is also observed [4–6]. Erosion of the electrode surface is explained by the heating of microheterogeneities due to an increase in current density in local areas to the melting temperature and rapid (explosive) evaporation of these microheterogeneities [1]. As a result, a cloud of dense plasma is formed on the surface of the electrodes with negative polarity before formation of a spark channel. In works [7, 8], devoted to the study of the mechanism of vacuum breakdown at high electric field strengths, it was established that one of the reasons limiting the electrical strength of a vacuum insulation is the effect of a strong electric field on the mechanical properties of the electrode surface. Calculations carried out in [8] showed that even in the unheated region, the size of which significantly exceeds the size of the explosive emission center, the cathode material is also exposed to destructive mechanical stresses. In this case, the primary appearance of the cathode spot during discharge in a vacuum and the formation of plasma near the electrode surface lead to multiple local destructions of its relatively smooth surface, including those at the periphery of the cathode spot.

Based on experimental and theoretical studies of breakdown in a vacuum, described by the authors of articles [7, 8]), in works [9, 10] it was suggested that the mechanism associated with the occurrence of destructive mechanical stresses should also take place during nanosecond breakdown in gases between electrodes with a small radius of curvature. Photographing the discharge with a high (up to 1.7 μm) spatial resolution in [9, 10] showed that thin luminous tracks (TLT) of particles appear in the interelectrode gap in both spark and diffuse discharges, moving along various trajectories. Shooting with a highly sensitive ICCD camera made it possible to establish that particles at a minimum distance from the electrodes are recorded with a delay of more than 1 μs, and their speed depends on the track diameter and is as high as ~ 40 m/s [9–11]. This speed is significantly less than the plasma expansion speed during explosive emission in a vacuum (~ 20 km/s), as well as the speed of a liquid metal jet at the cathode (~ 0.4 km/s) [12].

The results obtained in [9–11] aroused great interest and showed the need to continue studying the conditions for the appearance of TLT from electrodes. Attention to the observation of tracks is due to the lack of data on the registration of TLT during nanosecond diffuse discharges in a non-uniform electric field, see, for example, [13–17]. Note that during a spark discharge, a number of studies reported observation of the scattering of particles from the electrodes [8, 18], as well as the production of small-sized particles [19]. In addition, in [20], it was shown that tip erosion is observed during a corona discharge during generation of a series of Trichel pulses.

The aim of this work to study possibility of the appearance of tracks and define their shape under the conditions of a diffuse discharge in air, nitrogen, argon and helium, formed with small energy inputs.

Experimental setup and methods

The studies were performed using setup similar to that described in [9–11]. Schematic diagram of the setup is shown in Figure 1.

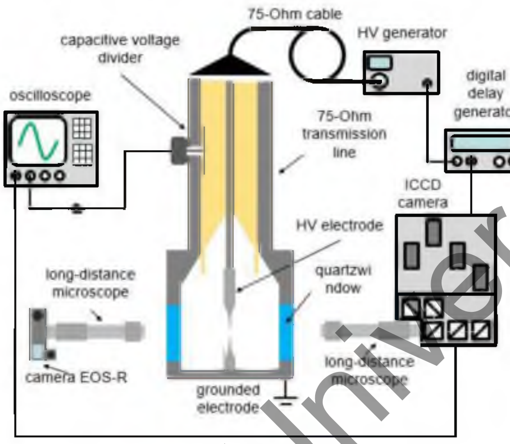

Figure 1. Block diagram of the experimental setup for studying particle tracks.

Voltage pulses from various high-voltage generators (HV), which are described in detail in [21], were fed to the input of the discharge chamber transmission line via a coaxial cable. The generators had positive or negative polarity. Minimum energy inputs into the discharge plasma were achieved using a positive polarity generator GIN-10 with a voltage pulse duration $\tau_{0.5} \approx 1$ ns (FWHM) and its rise time of $\tau_{0.1-0.9} \approx 0.7$ ns. The amplitude of the incident voltage wave in the transmission line was 11.6 kV. The energy in the pulse did not exceed 1.2 mJ. In the idle mode, the voltage across the gap doubled. Oscillograms of the incident and reflected from the gap waves of the voltage pulses and current through the gap are shown in Figure 2.

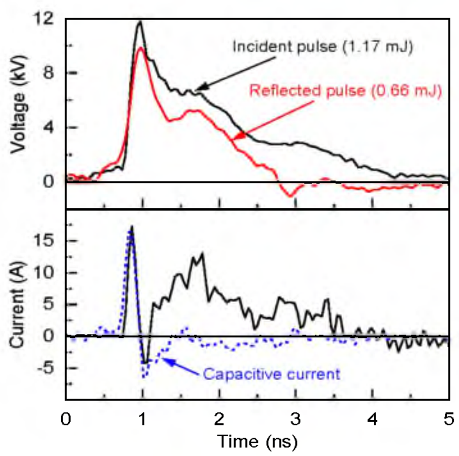

Figure 2. Oscillograms of the pulses of the incident and reflected voltage wave, as well as the current through the gap of the total and capacitive (dashed line).

The wave impedance of the transmission line with a built-in shunt was 75 Ohm. The resistance of the shunt was 8.7 mOhm. This shunt made it possible to record voltage waves incident on the gap and reflected from it, as well as to restore the voltage pulses reflected from the generator. The current through the gap was measured by a current shunt assembled from thin-fllm SMD resistors (Vishay Intertechnology), which was installed near the grounded electrode. The shunt resistance was 30 mOhm.

The radiative characteristics of the nanosecond discharge were recorded from the area between the electrodes, which were made from sections of sewing needles with a base diameter of 0.75 mm. The length of the needles was ~ 5.5 mm, and the rounding radii were ≈ 35 μm. Due to the low energy in the voltage pulse, the shape of the electrodes did not change significantly from pulse to pulse. We have not used before this generator to study particle tracks. The gap between the needles was 4 mm. Due to the lack of matching of the resistances of the gas-discharge, generator and transmission line, voltage pulses were reflected from the gap and from the generator. As a result, voltage pulses reflected from the generator returned to the gap with the opposite polarity. When using the GIN-10 generator, this delay was 22 ns. The main part of the energy was usually deposited in the discharge plasma during the first voltage pulse from the generator. Similar excitation modes of the diffuse discharge with other generators are described in detail in [9–11].

Waveforms of the incident wave of voltage and current pulses through the gap from the GIN-50-1 generator with the pulse duration of 13 ns are shown in Figure 3.

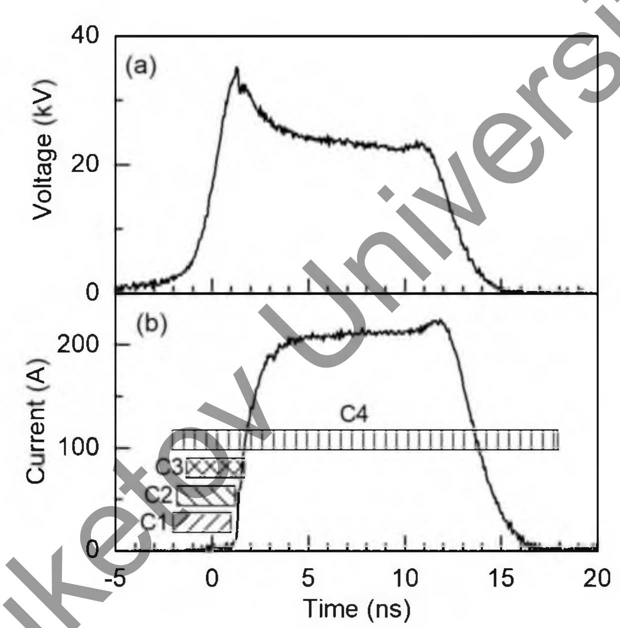

Figure 3. Waveforms of the voltage pulse on the gap and the current through the gap. Generator GIN-50-1. Rectangles C1, C2, C3 and C4 show the time of photographing the discharge plasma on different channels of the ICCD camera.

The maximum voltage pulse amplitude at the idle reached 50 kV. The maximum energy input into the discharge plasma during the first incident pulse were achieved due to the increase in the voltage pulse duration with this generator. The positive polarity voltage pulse duration of this generator at half-height was $\tau_{0.5} \approx 13$ ns and its front was $\tau_{0.1-0.9} \approx 4$ ns.

The signals from the shunts were recorded by a Tektronix MSO64B oscilloscope (8 GHz, sampling frequency 20 samples/ns). The discharge plasma glow images were taken with a Canon EOS 2000D SLR camera (24.7 MP pixel count, 22.3×14.9 mm matrix size, 3.72 μm pixel size), which was equipped with a K2 DistaMax long-focus microscope (Infinity Photo-Optical Company) with a CF-3 lens. The microscope in this configuration provided a magnification of 3.56 with a maximum resolution of 1.7 μm. The camera exposure time was usually 0.5 s, and the sensitivity was 40000 ISO. In addition, a four-frame ICCD camera HSFC PRO with frame duration of 3 ns was used to photograph the discharge. This ICCD camera and generators could be switched on with an accuracy of about 10 ps. This made it possible to record changes in the plasma glow during the discharge over a time of tens of picoseconds. The shaded rectangles show the switching time of individual frames of the ICCD camera are shown in Figure 3. An HR2000+ES spectrometer with a 13 light guide (range 200–1150 nm; optical resolution ≈ 0.9 nm) with a known spectral sensitivity was used to measure the discharge emission spectra. The discharge chamber had two side windows made of KU-1. Photographing the discharge and measuring the emission spectra were carried out in the absence of extraneous lighting.

The gas discharge chamber was evacuated by a forevacuum pump and filled with atmospheric air with a relative humidity of 23 %, or nitrogen, argon, helium. The studies were carried out at a pressure of ≈ 760 Torr.

Results and Discussion

With the GIN-10 generator, the studies of discharge glow in air, nitrogen, argon and helium were carried out at minimum energy inputs, which in our conditions were determined by the short duration of the voltage pulse (~ 1 ns at half-height) and its amplitude (~ 11.6 kV in the incident wave). In addition, similarly to [9–11], the studies were carried out at energy inputs with higher energy inputs by 5 times or more with the GIN-50-1 generator and generators providing negative polarity of the voltage pulses. Breakdown of the gap filled with air, nitrogen or argon at pressure of 760 Torr with the GIN-10 generator was usually observed at a voltage pulse amplitude close to the maximum. Due to short rise time duration of the voltage pulse, a peak of the capacitive current was stably evident on the oscillogram of the current through the gap, which exceeded in its amplitude the conduction current, Figure 2. The energy, deposited into the gas in the first voltage pulse from the generator, in air was about 0.5 mJ and changed slightly (~ 10 %) from pulse to pulse.

As is known, before the breakdown of the gas-filled gap, the idle mode is realized, the resistance of the discharge plasma decreases due to development of the ionization processes in the gas. If forming a diffuse discharge with optimal voltage on the gap, a matched mode can be realized for some time, in which the plasma resistance in the gap is equal to the resistance of the generator transmission line. However, in the case of nanosecond voltage pulse, the process of matched energy input usually takes only a part of the voltage pulse duration. For these reasons, it is impossible to achieve complete matching of the discharge plasma resistance and the GIN-10 generator impedance. Figure 2 shows oscillograms of voltage and current pulses in the gap filled with atmospheric air, which consisted of capacitive current and conduction current. Photographs of the discharge plasma glow in air and nitrogen under conditions of track appearance at low energy inputs are shown in Figure 4 and Figure 5, respectively.

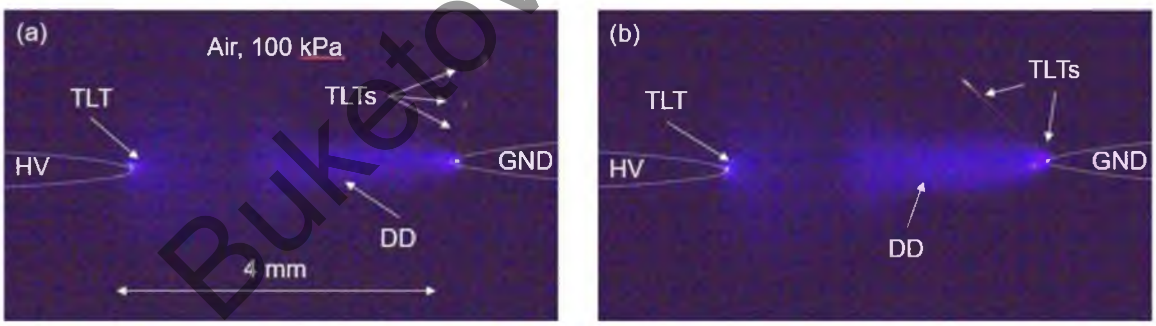

Figure 4. Photographs of the integral discharge glow in air, obtained for one voltage pulse for two different switches of the GIN-10 generator, (a) and (b). HV — high-voltage electrode, TLT — thin luminous tracks, DD diffuse discharge, GND — grounded electrode.

The discharge mode with the formation of a diffuse discharge and TLT in air for two different voltage pulses is shown in Figure 4. Tracks are visible at both electrodes, and the TLT with the greatest length were recorded at the grounded electrode, which had a negative polarity when arriving the first voltage pulse. A feature of the glow of tracks in air at low energy inputs was the greatest intensity at their end. When the energy inputs are increased to >5 mJ, see also works [9–11], most tracks in air and argon had approximately the same glow brightness along their length.

When the discharge was formed in nitrogen or in helium, in contrast to the discharge in air, the intensity of the track radiation was maximum at the bright spots on the electrodes and slowly decreased with distance from the spots, see Figure 5.

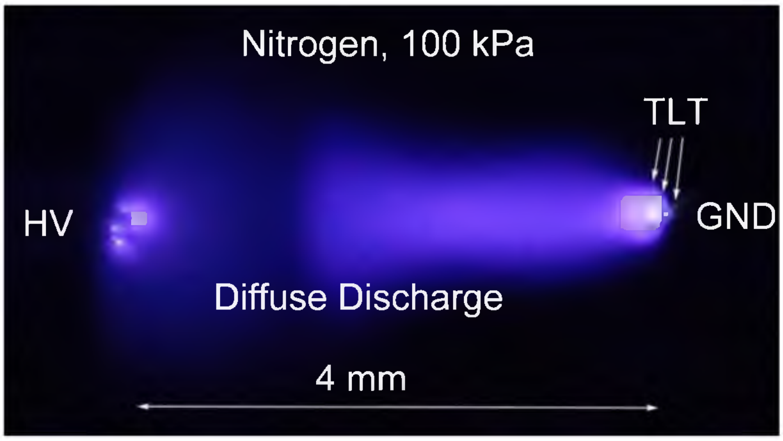

Figure 5. Photographs of the integral discharge glow in nitrogen, obtained for one voltage pulse of the GIN-10 generator. HV — high-voltage electrode, TLT — thin luminous tracks, GND — grounded electrode.

Moreover, the TLT in nitrogen had higher glow brightness than in helium, but lower than in air. It was not possible to register particle tracks in argon with the GIN-10 generator. However, TLT were observed with the GIN-50-1 generator at higher energy inputs and in [9] with the GIN-55-01 generator, when the gas pressure was decreased.

The dynamics of the formation of a diffuse discharge before the gap is closed by a spark channel is shown in Figure 6.

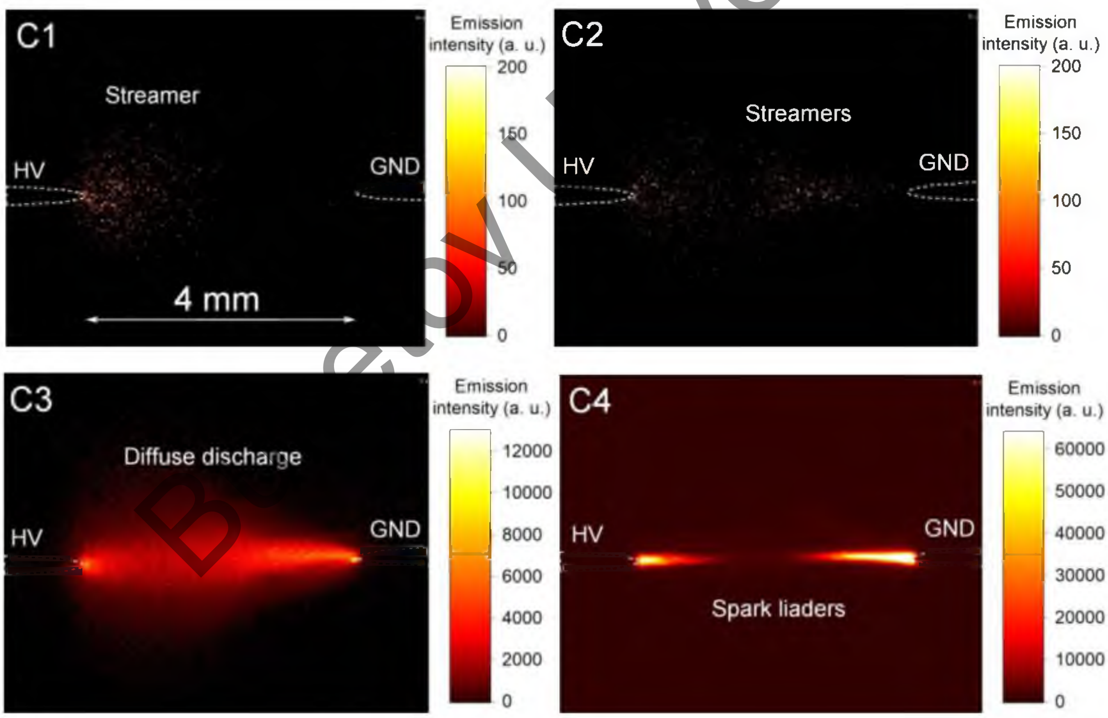

Figure 6. Images of the discharge in air obtained with the ICCD camera for the first voltage pulse from the GIN-50-1 generator, which is shown in Figure 3, where individual frames of the ICCD camera are shown as shaded rectangles. HV is the high-voltage electrode, GND is the grounded electrode.

The dynamics of the formation of the first spherical streamers is described in detail in [22, 23]. Figure 6 demonstrates the appearance of the first spherical streamer at the high-voltage electrode. Then the second streamer is formed at the grounded electrode. The streamers collide, and a diffuse discharge is formed in the gap, see frame C3, as well as the integral photographs in Figure 4 and Figure 5. When the voltage pulse duration and (or) its amplitude are increased, spark leaders grow from the electrodes. In this case, see frame C4, it can close the gap and forms a spark channel as expected, see, for example, [6, 9]).

As expected with HR2000+ES spectrometer, the bands of the second positive system (2^+) of molecular nitrogen dominated in the emission spectra during diffuse discharge stage in air and nitrogen, which is due to the high electric field strength across the gap during its breakdown by the voltage pulse with sub-nanosecond rise timed. The spectral density of the radiation energy of the main bands of the 2^+ nitrogen system was several orders of magnitude greater than that of the bands of the first positive (1^+) nitrogen system. It was not possible to register the emission spectra of the TLTs under these conditions. The difficulties in registering the emission spectra of the tracks can be explained by their thermal nature and, accordingly, by the large width of the emission spectra of the TLT. The emission of tracks during the expansion of particles from the electrodes is also affected by the high temperature of the bright plasma spots on the electrodes. These spots are known to be formed due to the explosive emission of electrons [1]. It follows from the data obtained that both processes take place during the heating of the particles that form the tracks. In nitrogen, see Figure 5, and helium, the brightness of the tracks decreased with distance from the electrodes, while in air it was maximal at the end of the tracks, see Figure 4. Apparently, particles from the electrodes can also be heated during collisions with molecules and gas atoms, but this process is less effective.

The studies performed support the hypothesis put forward in [9, 10]. The observed TLTs are traces of hot metal particles that fly out of the electrode surface in the area of its contact with dense plasma. Initially, plasma is formed during heating and thermal explosion of microinhomogeneities due to an increase in the current density in these places. The plasma created strengthens the electric field on the electrode surface. When the energy input is low, the tracks were found to have a greater length when initiated from an electrode with negative polarity. Note, that in our experiments the greatest electric field strength was achieved on the high-voltage electrode upon arrival of the first pulse from the generator. The grounded electrode was surrounded by the walls of the discharge chamber, which weakened the electric field at the tip, see Figure 1. However, the tracks were mainly generated from this electrode and spread over large distances.

Conclusions

In this paper, we study the formation of thin luminous tracks in the gap with electrodes having a small radius of curvature in diffuse discharge in air, nitrogen, argon, helium at low energy inputs into the gas. It was found that TLTs are formed mainly from the negative polarity electrode and their length becomes shorter with decreasing energy inputs into the discharge plasma. It was shown that the ends of the tracks have the greatest brightness in air, which can be explained by their additional heating during the oxidation of particles that start from the electrodes. The intensity of track radiation in nitrogen and helium is maximal near bright spots on the electrodes and decreases with distance from them, which indicates a decrease in the temperature of the particles, forming the tracks. TLTs in discharge in argon could not be registered, when energy input is low.

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В.Ф. Тарасенко, Д.В. Белоплотов, Д.А. Сорокин, А.Н. Панченко

Газдардағы наносекундтық разрядтар кезінде қисықтық радиусы аз электродтардан жылдам бөлшектер мен металл булары

Біркелкі емес электр өрісі бар саңылауларда жоғары электр өрістеріне (>1 МВ/см) қысқа кернеу импульсі арқылы қол жеткізіледі, олар катодта оң иондардың жиналуымен және плазманың түзілуімен күшейеді. Вакуумдық разрядтың белгілі эксперименттік және теориялық зерттеулеріне сүйене отырып, біз электродтардың беткі қабатындағы деструктивті механикалық кернеулердің механизмі газдардың наносекундтық ыдырауы кезінде де жүруі керек деген болжам жасадық. Мақалада атмосфералық қысым кезінде разрядтық саңылаулар ауамен, азотпен, аргонмен және гелиймен толтырылған кезде қисықтық радиусы аз екі электрод арасында пайда болған диффузиялық разрядты плазманың сәулеленуі зерттелді. Наносекундтық кернеу импульсінің ұзақтығы және газға түсетін энергия мөлшері <1 мДж/см^3 болған кезде электродтардағы жарқын дақтардан, соның ішінде олардың бетіне тік бұрышта орналасқан бөлшектердің іздері тіркелді. Жолдардың ұзындығы электродтың полярлығына байланысты екендігі және ауадағы төмен энергия кірістері кезінде жолдар жарқыраған аймақпен аяқталатыны көрсетілген. Төрт түрлі газдағы (ауа, азот, аргон және гелий) разрядтар кезінде сәулеленудің ең жоғары қарқындылығы ауада түзілетін жолдарда болатыны анықталды. Осы нәтижеден, сондай-ақ жүздеген микросекундтық тректердің жарқыл импульстарының тіркелген ұзақтығынан ауада таралу кезінде трек ұштарының сәулелену жарықтығының жоғарылауы ұшатын бөлшектердің оттегімен әрекеттесуі кезінде электрод материалының қызуымен анықталады.

Кілт сөздер: ұшынан ұшына дейінгі саңылау, наносекундтық импульстар, диффузиялық разряд, бөлшектердің іздері.

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Быстрые частицы и пары металлов с электродов, имеющих малые радиусы кривизны, при наносекундных разрядах в газах

В промежутках с неоднородным электрическим полем при коротком фронте импульса напряжения достигаются высокие электрические поля (>1 MV/cm), которые усиливаются за счёт накопления у катода положительных ионов и образования плазмы. На основании известных экспериментальных и теоретических исследований вакуумного разряда нами было высказано предположение, что механизм разрушающих механических напряжений в поверхностном слое электродов должен иметь место и при наносекундном пробое в газах. В статье при заполнении разрядных промежутков воздухом, азотом, аргоном и гелием атмосферного давления исследовано излучение плазмы диффузного разряда, формируемой между двумя электродами с малым радиусом кривизны. При наносекундной длительности импульса напряжения и энерговкладах в газ <1 mJ/cm^3 зарегистрированы треки частиц, вылетающих из ярких пятен на электродах, в том числе под прямым углом к их поверхности. Показано, что длина треков зависит от полярности электрода, и, что при малых энерговкладах в воздухе треки заканчиваются более яркой областью свечения. Установлено, что наибольшую интенсивность излучения при разрядах в четырёх различных газах (воздух, азот, аргон и гелий) имеют треки, которые формируются в воздухе. Из этого результата, а также из зарегистрированной длительности импульсов свечения треков в сотни микросекунд следует, что усиление яркости излучения окончаний треков при распространении в воздухе определяется нагревом материала электрода при взаимодействии вылетающих частиц с кислородом.

Ключевые слова: промежуток остриё–остриё, диффузный разряд, треки частиц.

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