LOCAL AND NONLOCAL CRITERIONS OF RUNAWAY ELECTRONS IN SOLID GASES AND DIELECTRICS UNDER ACTION OF HIGH VOLTAGE PULSES BY SHORT WAVEFRONT

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Present article is devoted to discharge processes in solid gases and dielectrics under influence on discharge gap the high voltage nanosecond pulses. Are considered the local and non-local criterions of run off electrons in gases and formation on the discharge gap the powerful electron beams. Are considered a conversion of diffusive volumetrical discharge to constricted discharge on different interelectrode distance and electrodes geometry, the physical processes in solid dielectrics under influence the high voltage nanosecond pulses. It is presented a quantitative correlations between the electrical pulse parameters, dielectrics properties and space-charge characteristics of pulsed discharges.

1. Intoduction

Last time is given enormous attention to development of high voltage pulsed technique for realization of the different researches and applied purposes. At the most fields of industry and technique is observed transition from microsecond high voltage pulses to nanosecond ones. Nano and subnanosecond electrical pulses by on-peak power from MVt up to TVt are used in a number of the most areas of modern technique such as relativistic microwave electronics, super wide-band radio-location, electromagnetic reaction, research of electromagnetic compatibility of the complex systems, underground radio-location, lasers and accelerators power systems and so on [1]. Powerful short pulses are also used in a number of modern developmental physics areas such as controlled nuclear fusion and other large-scale physical experiments.

Particular interest presents study of high voltage nanosecond discharges and their influence on electro physical properties of solid dielectrics [2] and showing up the new phenomena earlier no metering in that materials under influence of high electrical fields.

Development of nanosecond pulsed discharge process is accompanied by infraction of electrons distribution function by energy and appearance of run off electrons capable to realize a collision ionization.

The run off electrons phenomenon in plasma is known a long time ago [3] were carried out the numerical computations [4,5] and analytic treatment for low fields [6]. This phenomenon has an essential importance for diagnostics and admixture's energy-balance in plasma of tokamacs [7].

2. Theory and experimental results in solid gases

Appearance of run off electrons in gases takes on special significance in view of getting the powerful subnanosecond electron beams with record big current amplitude [8].

Space structure of discharge gap's glow during the pulsed discharge process is defined by some factors such as the electrodes geometry, pressure and gas type, inductive and capacitive parameters of generator, disruption voltage of discharger – peaker [9].

In spite of rapid growth of experimental researches and technical applications [10] of nanosecond gas discharges, transition to the new time scale doesn't entail the corresponding revision of fundamental positions of breakdown classical models developed for conditions near the static ones [10]. But in article [11] are determined the new understanding of nanosecond pulsed discharges.

An electrical breakdown models in solid gases differed in many respects from each other, sometime radically, nevertheless have general fundamental feature: they are local. It means that on given space time *(r, t)* the average statistical value such as an electrons energy - ε_e, ordered motion speed - v_-, Townsend ionization factor - α are determined by local field at the same point $E(r,t) = E_o + E_p(r,t)$, where E_o and $E_p = E_{p+} + E_{p-}$ - external field and space charge intensities.

To local models are related to Townsend avalanche generation with γ-processes on cathode and different modifications of single-avalanche streamer model that describes the breakdown processes in solid gases corresponding to right part of Pashen's curve ($pd >> (pd)_{min}$), where the space charge Z_{cr} and time t_{cr} avalanche progress scales satisfy to correlations:

$$Z_{cr} = \alpha^{-1} \cdot ln\, N_e^{\kappa p} \leq d \tag{1}$$

$$t_{cr} \leq \frac{d}{\upsilon_-} \tag{2}$$

where N_E^{cr} - electrons quantity on the critical avalanche, *d*- interelectrode distance.

In classical streamer model can emphasize three main parts: an electrical field strengthening on electron avalanches front and streamers as result of their polarization $(E_f = E_o + E_p)$; gas ionization by photons ahead of front; prevalent ionization processes in gas volume in comparison with cathode emission.

As result of field strengthening the electrons energy is become more than $\varepsilon (E_o)$, balanced intensity of external field E_o owing to which the ionization processes are intensified.
A volumetrical photoionization explains the streamers big propagation speed $(>>v_-(E_o))$ that is necessary for propagation of cathode streamer. Is opened to question the nature of radiation initiating the second ionization centers out of initial avalanche [12, 13]. On this article is considered all these questions.

In case of big interelectrode distance even for strong fields, where field intensity exceeds a critical value, Townsend's ionization mechanism is also true and is taking place the γ- processes on cathode and streamers formation by which are described the ionization processes in gases corresponding to right part on Pashen's curve $(pd>> (pd)_{min})$.

At that for determination of an average energy E^*, it is necessary to take into account a number of electrons by $E>E_{cr}$, as is shown below:

$$\frac{d\left(N_e E^*\right)}{dx} = eEN_e - F\left(E^*\right)N_e \qquad (3)$$

$$\frac{dN_e}{dx} = \alpha_i \cdot N_e \qquad (4)$$

$$\frac{dE^*}{dx} = eE - F(E^*) - \alpha_i E^* \qquad (5)$$

where α_i - a collision ionization factor, E^* - electrons average energy.

In formula (5) we can see that even by full neglect of electrons braking in gas $F(E^*)=0$, an average energy of electrons is restricted.

$$E^* < E^*_{\max} = \frac{eE}{\alpha} \qquad (6)$$

By sufficiently big over voltages $(\Delta>>1)$ development of gas discharge process is differed from classical discharge forms in gases.

In strongly overstrained discharge gaps an avalanche-streamer transition is realized on the length of $z_{cr} \sim 100$ mcm. As a result of that is formed a plasma cloud by big conductivity. In strong electrical fields this cloud is polarized.. Then ionization is developed by electrons, escaped from cloud and accelerating in space charge zone. Part of these electrons have very big energy comparable with full kinetic energy $eU=eEd$ and uninterruptedly accelerated up to anode. These electrons efficiently radiate the brake quantum ionizing gas in whole discharge gap and beat out the electrons from electrodes. As a result of that number of the elementary "accelerators" is grown.

At that on fig.1 is shown the Pashen's curve division on three zone: space upper left part curve corresponds to the run off electrons, space between the left and right parts on curve corresponds to electrons multiplication and space below the right part corresponds to electrons drift those couldn't multiply

Were carried out the experiments in uniform and no uniform electrical fields [14] on big pressures and different gases (nitrogen, air, helium, neon, argon, krypton) without ionization source.

In all gases in no uniform electrical field at the atmospheric conditions under influence of high voltage nanosecond pulses were received the high specific energy up to до $1 J/cm^3$ and electron beams by record current amplitude.

The run off electrons ensure the propagation speed of ionized field to anode and attendant X-radiation ionizes gas and causes a photoelectric effect on cathode stipulated for motion the cathode streamer.

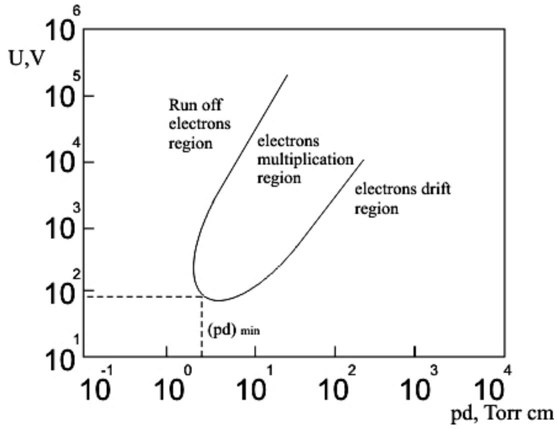

Fig. 1. Dependence of the critical breakdown voltage *($U_{кр}$)* from multiplication an interelectrode distance between the electrodes – *d* on pressure – *p (pd)*, Pashen's curve.

Our researches were carried out by means of high voltage nanosecond generator on 100 kV with short pulse front 2 ns. Block scheme of an experimental assembly is shown on fig.2.

Voltage pulse was supplied from generator 1 to high voltage electrode – cathode 3 inside of vacuum chamber 2 at atmospheric pressure – P=760 Torr and higher were used two cathodes by different radius of curvature – $r_c \sim$ 1-6 mm. For getting a volumetrical pulsed discharge glow at atmospheric pressure and higher on cathode by diameter ∅ 1 mm is installed fluoroplastic cap 6. As an anode is used a copperplate 4 and a metal screen 5. Interelectrode distance ~d is changed over the range ~ 3-10 mm. For photographing of the high speed pulsed discharge glow is used an electron-optical camera 7. The total current of pulsed discharge by current shunt 8 is registered on high-frequency oscillograph TDS-5104. Electron beam's current by Faraday cup and current shunt 9 is also registered on high-frequency oscillograph TDS-5104.

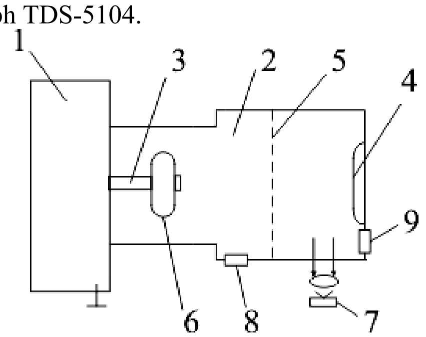

Fig.2. Block scheme of an experimental assembly 1- high voltage nanosecond generator, 2- vacuum chamber, 3- cathode, 4 - anode, 5- metal screen, 6- fluoroplastic cap, 7- electron-optical camera, 8 – shunt for measuring of discharge total current, 9 – shunt for measuring of electron beam's current.

The cathode and cathode plasma are the sources of run off electrons in air at atmosphere pressure. Dispersion on gas molecules strongly influents on the space distribution of run off electrons. In case of pointed cathode, the interelectrode distance – *d* greatly influents on the width of run off electrons beams. By increase the - *d* up to 10 mm beam's diameter reaches ∅ ~3cm. If there are some channels in pulsed discharge taking place on developed work surface, the channels quantity are equal to beams quantity in electron stream behind the anode. The streams structure respond to emitting centers distribution. Plasma bunch on cathode is transformed into constricted channel growing deep into discharge gap by stream of run off electrons. By statistics of that interaction and also initiation of electron avalanches is explained a variety of discharges space forms. When overvoltages factor $\Delta >>1$, the gas breakdown is initiated by auto electronic emission and the first avalanche reaches a critical size near the initialization point (Z_{cr}~*100* mcm<< d). As a result is happened the field strengthening of positive space charge E_{p+} and auto electronic emission. Therefore, when $\Delta>>1$, the emissive processes play a fundamental role in ionization propagation towards cathode. The high penetrability of run off electrons and X-ray emission reduces to solid gas ionization far off the first ionization center and discharge loses its compact form and has diffusive or multi-channel character. By big overvoltages in solid gases in atmosphere pressure the complex space structure of the nanosecond volumetrical discharges as the constricted channels is explained by electrons acceleration in space charge field getting the possibility to accelerate up to anode.

These electrons radiate the quantum ionizing the gas in whole discharge gap and battered the electrons from electrodes. The space structure of discharge gap's glow as mentioned is determined by some parameters such as an electrodes geometry, interelectrode distance – *d*, gas pressure - *p*, parameters of generator. The photography of discharge gap's glow for different distance value – *d* and electrodes geometry are presented on figures 3-7. On figures a flat copperplate and the metal screen is as an anode and as a cathode is a metal rod by different radiuses of curvature – r_κ ~1-6mm. On fig. 3 is shown that in atmosphere pressure, U_{gen}=100kV and *d*=10 mm is realized the diffusive volumetrical discharge

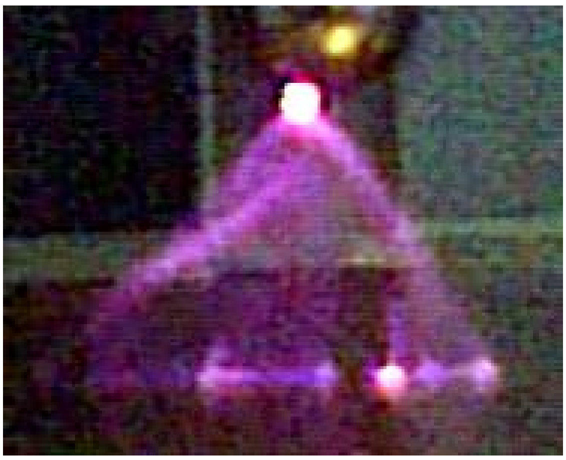

Fig.3. r_k=6mm, anode - copperplate, U_{gen}=100kV, *P*=760 Torr, interelectrode distance *d*=10 mm

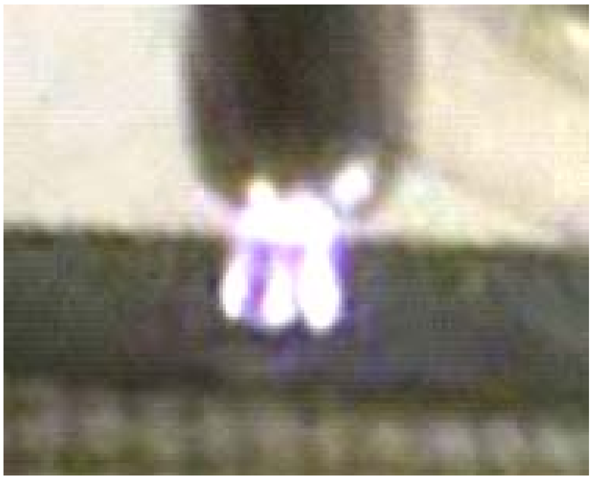

Fig.4. r_k=6 mm, anode - metal screen, U_{gen}= 100 kV, *P*=760 Torr, interelectrode distance *d*=5 mm

On the cathode are formed the plasma bunches by visible dimension l_p ~ 2 mm<< *d*, but remaining space up to anode is filled up by diffusive glow. The cathode plasma formations significantly are not uniform.

On fig. 4 is shown that at atmosphere pressure and interelectrode distance – *d*=5 mm there are some plasma bunches on the cathode and is realized transition from diffusive volumetrical discharge to constricted discharge and constricted channels quantity is equal to plasma bunches quantity on cathode

We have to note, when we decrease an air pressure, the plasma bunches dimension on cathode is grown and luminosity is decreased.

When *P< 0.5 Torr* the discharge phenomena on the case of planar electrodes with developed work surface aren't observed, but if cathode is a metal rode by different radiuses of curvature, the plasma bunches are appeared on its surface and their size is significantly smaller in comparison with atmosphere *conditions - P*=760 *Torr.*

On Fig. 5 when the cathode radius of curvature is smaller r_κ ~1mm*, an* interelectrode distance *d*=10 mm*,* U_{gen}= 100 kV and *P*=760 *Torr, an* intergrowth of the bright constricted channel and overlap of whole discharge gap is observed.

Fig.5. r_k= 1 mm, anode- metal screen, U_{gen}=100 kV, *P*=760 Torr, interelectrode distance d=10 mm

Fig.6. r_k= 1 mm, anode- metal screen, U_{gen}=100 kV, P=760 Torr, interelectrode distance d=3 mm

On Fig. 6 by decrease of an interelectrode distance up to d=3 mm the enlargement of discharge channel is observed. Diffusive cover in that case is not appeared.

In case of sharply no uniform field is fixed only one bright channel and plasma bunch. By increase of the field uniformity the channels and plasma bunches quantity are grown.

On fig. 7 is shown a glowing ball, formed by pressures more than atmospheric *(P=3.5* atm) and interelectrode distance – *d=3* mm. By means of fluoroplastic cap, put on etal rod by diameter ∅ 1mm and high pressure in vacuum chamber the pulsed discharge channel looks like glow ball.

By multiple overvoltages in volumetrical discharges in air ionization emission reaches the light speed and the current pulse with a high rate of pulse rise ~ 10 *TA/s* is realized. In that case a pulse front is τ_I < 0,5ns and upper bound of current is I_m ~1,5 kA. By decrease of the interelectrode distance – *d* the volumetrical discharges pass into constricted channel and the current amplitude I_m and channels conductivity are grown.

Also we have to note the importance of the breakdown delay time parameter – t_d relatively to moment of voltage pulse supply from generator that characterizes a speed of ionization processes development.

When d < 10 *mm* and U_{gen} > 180 *kV* independently from cathode geometry in solid gases a big conduction current is already appeared on the front of voltage pulse and $t_d < \tau_I < \tau_{gen} < 0{,}6ns$, where τ_I is an acceleration time of voltage pulse at the discharge gap.

Fig. 7. r_k= 1 mm, anode - metal screen, U_{gen}=100 kV, P=3,8 atm, interelectrode distance d=10 mm

So speed of ionization propagation $V_I > d/t_d > d/\tau_{gen} > 2.5\cdot10^9 cm/s$ is more than speed of streamers propagation [15, 16]. When U_{gen}< 180 *kV* in relatively uniform field we can register the breakdown delay interval parameter – t_d ~2 *ns* for cathodes radius of curvature r_c ~20 *mm*. By decrease of pressure this parameter t_d is grown.

Thus the mechanism of discharge development in solid gases by big overvoltages can be presented in the following way. As a result of auto electronic emission the initial electrons from cathode form an avalanche that on pulse front during some picoseconds on the length Z_{cr}~100mcm transforms into anode streamer. Before the voltage pulse reaches the maximal value, an electrical field intensity on the streamer front reaches the critical value E_{cr}.. On that time on streamer front are formed the run off (high power) electrons and is realized the mechanism of polarized self-acceleration reducing to generation the powerful subnanosecond pulses of electrons by anomalous energy (100-200keV). These electrons ionize a gas and form the volumetrical discharges on discharge gap in relatively weak non-uniformity field. In strongly no uniform fields the volumetrical discharge is only formed as a result of gas ionization by run off electrons stream. Because an interelectrode distance – $d >> Z_{cr}$ the cathode discharge is caused only by photoelectric effect. Local field strengthening on cathode by positive space charge reduces to formation of plasma bunch during t_d < 1ns on the first avalanche place. From this moment are begun formation and development of cathode spot and exploding processes on cathode by transition to exploding electronic emission. On sufficiently small interelectrode distance the plasma bunch is constricted and advanced over ionized gas by run off electrons. As result the high local intensity of electrical field on the channel head where is concentrated a negative space charge, this channel is accelerated as a single whole. In spite of the fact that reached power density, input in discharge gap is ~100MVt/cm^3 plasma is remained low-temperature, weakly ionizated in all discharges development stages because there is the weak coupling of run off electrons with gas.

Thus on big overvoltages the run off electrons effect plays a fundamental role in breakdown mechanism of pulsed discharges in solid gases. Participation of run off electrons in breakdown process in solid gases is determined by displacement of minimum on Pashen's curve *U(pd)* to right by overvoltage growth (shortening the pulse front τ_{gen}) for big pd.

3. Pulsed discharge researches in solid dielectrics

By influence of high voltage nanosecond pulses on solid dielectrics is also observed a formation process of high power electrons. During an influence of powerful short pulses it is necessary to note the propagation speed of pulsed discharge, parameters of plasma condition in discharge channel, its geometrical sizes and others. Already it is insufficient to know only parameters of discharge gap and high voltage pulse.

The direct measurement of propagation speed of discharge channel by electron-optical chronogram was determined that the sonic speed is a limit for propagation speed of discharge channel from cathode and anode i.e. $v_c < c_o < v_a$ where v_c– discharge speed from cathode, v_a- discharge speed from anode, c_o - sonic speed in solid dielectrics [17].

Change of that boundary "from above" and "from below" by change the pulse parameters *(U, dU/dt)* were unsuccessful.

Transition mechanism from subsonic initial channel to supersonic anode channel demands an especial study.

Discharge speed from anode - v_a is mainly determined by origin discharge voltage U_0 and corresponding momentary value *dU/dt*, but discharge speed from cathode - v_c depends only on U_0. In that case an influence of interelectrode distance – *d* and momentary value *dU/dt* is absent. This can be related with instability of dielectrics phase boundary with its melt. Supersonic speed of change of boundary curvature under influence of very high electrical fields reduces to formation the shock wave that is result of turbulent energy-release by electron injection from valence band to conducting band and formation the complex "shock wave + energy-release zone" named as electron detonation.

Run off electrons took part in collision ionization of valence band in solid dielectrics have anomalous energy and just only they explain the physical mechanism of turbulent electron injection to conducting band under influence of high voltage nanosecond pulses on these materials. As result of this is formed dense non-ideal plasma by big pressure on self-destruction which is liberated energy accumulated in an ionic subsystem.

Ionization degree of electron injection will be determined by correlation [18],

$$\chi_e = \omega \frac{\Delta}{v_a} \tag{7}$$

where $\omega = \dfrac{n}{N}$ - ionization probability c^{-1}, n – quantity of electron-hole pairs formed in time unit and volume unit, N – valence electrons quantity. Ionization probability ω depends from forbidden gap and defined as

$$\omega = \frac{n}{N} = \frac{\left(eEd^*\right)^2}{2\pi h E_D^*} \exp\left(\frac{Ed^*}{eEd^*} \ln\frac{1}{\alpha}\right) \tag{8}$$

where α- ratio of valence band to conducting band, E_D^* and d^* - accordingly an effective value of forbidden gap and lattice constant by shock compressing.

By compressing of solid dielectrics dependence between forbidden gap and plasma pressure is presented by following formula:

$$E_D^* = E_{D_0} - a_p \cdot p \tag{9}$$

where $a_p = \gamma \cdot \kappa$ - pressure factor $J*Pa^{-1}$, κ – compressibility factor, γ - proportionality factor.

These expressions allow to quantitatively estimating the dependence of plasma pressure *P*, ionization factor ω and E_D^* from speed of an electron detonation wave in solid dielectrics.

Ascertained regularities allow us to use conceptions and methods of high- density energy physics for description the dynamics and matter state parameters in discharge channel on transition front from subsonic to supersonic speed.

It is evident that speed of this process at the different dielectric mediums and its initial parameters *(U_0 , dU/dt)* present a big interest.

It is necessary to carry out a number of experiments and theoretical study for proper quantitative consideration an influence of compressibility on electron injection process in solid dielectrics. First of all it is concerned to study an influence of plasma pressure on electron structure of large band dielectrics. It will allow to more rigorous determination of pressure factors value a_p. Can say that here this dependence will be nonlinear in a large pressure interval.

So were determined the quantitative correlations between the electrical parameters of process, physical properties of dielectrics, matter parameters in energy-release zone and space-charge characteristics of pulsed discharges under influence of high voltage nanosecond pulses on solid dielectrics.

4. Conclusion

In presented article are considered the physical processes in pulsed nanosecond discharges in solid gases and dielectrics. The local and non-local criterions of run off electrons (high power) in solid gases are shown.

To produce the pulsed discharge figures by different electrodes geometry and interelectrode distance. Is shown transition of volumetrical diffusive discharge to constricted discharge formed due to run off electrons created on cathode plasma bunches.

The electrical breakdown process in solid dielectrics under influence of high voltage nanosecond pulses, electron injection process from valence band to conducting band by run off electrons by anomalous energy were considered.

Was determined the quantitative correlations between the pulse electrical parameters and physical properties of solid dielectrics and their interference on each other. Consideration of that interference can produces to correction of existent and detection the new before no registering phenomena in solid dielectrics.

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YÜKSƏK GƏRGİNLİKLİ QİSA İMPULSLARIN BƏRK CİSİM HALINDA OLAN DİELEKTRİKLƏRƏ VƏ YÜKSƏK SIXLIQLI QAZLARA TƏSİRİ ZAMANI ELEKTRONLARIN HƏRƏKƏTİNİN LOKAL VƏ QEYRİ-LOKAL KRİTERİYALARI

Məqalə yüksək sıxlıqlı qaz mühiti və bərk cisim halında olan dielektriklərdə, qazboşalması aralığına yüksək gərginlikli nanosaniyə impuls gərginlikləri vasitəsilə təsir etdikdə, qazboşalması proseslərinin tədqiqinə həsr olunmuşdur. Elektronların qaz mühitində hərəkətinin lokal və qeyri-lokal kriteriyalarına və qazboşalması aralığında güclü subnanosaniyə elektron dəstinin əmələ gəlməsinə baxılmışdır. Bərk cisim halında olan dielektriklərdə katod və anod yaxınlığında plazma kanalında və oxun dinamikasının əmələ gəlməsi şərtləri müəyyənləşdirilmişdir. İmpuls qazboşalmasının elektrik parametrləri, dielektrikin xüsusiyyətləri və termodinamik xarakteristikaları arasında əlaqələr təqdim olunmuşdur.

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ЛОКАЛЬНЫЙ И НЕЛОКАЛЬНЫЙ КРИТЕРИИ УБЕГАНИЯ ЭЛЕКТРОНОВ В ПЛОТНЫХ ГАЗАХ И ТВЕРДЫХ ДИЭЛЕКТРИКАХ ПРИ ВОЗДЕЙСТВИИ КОРОТКИХ ИМПУЛЬСОВ ВЫСОКОГО НАПРЯЖЕНИЯ

Настоящая статья посвящена разрядным процессам в плотных газах и твердых диэлектриках при воздействии на разрядный промежуток высоковольтных наносекундных импульсов высокого напряжения. Рассмотрены локальный и нелокальный критерии убегания электронов в газах и формирование в газовом промежутке мощных субнаносекундных электронных пучков. Анализируются случаи перехода диффузного объемного разряда в контрагированный разряд при различных конфигурациях электродов и расстояниях между ними Сформулированы условия образования плазменного канала и его динамики у катода и анода в твердых диэлектриках. Представлена количественная связь между электрическими параметрами импульсного разряда, свойствами диэлектрика и термодинамическими характеристиками.

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