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Using the field ionization model to describe pulsed breakdown of solid dielectrics

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An evaluation technique is proposed for calculating the volt-second characteristics of the breakdown of solid dielectrics based on the field ionization model. A procedure is given for estimating the radius of the streamer head depending on the voltage and geometric characteristics of the system. The correspondence of the evaluation formulas data with the results of a model three-dimensional finite element numerical calculation is demonstrated. For some polymer materials, the parameters of the field ionization model are determined A satisfactory agreement between the volt-second characteristics obtained in the estimation calculation and the experimentally observed ones at nanosecond breakdown times is shown.

Keywords: field ionization model, volt-second characteristic, dielectric impulse strength, charge carrier.

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Introduction

During nanosecond pulsed breakdown of dielectrics, the discharge characteristics significantly depend on the geometry of the electrodes. The largest number of experimental results in this area were obtained in „point-plane geometry“. This is largely due to the ease of implementation and lower discharge voltages compared to breakdown in a nearly uniform field.

For most polymer dielectrics, the tip polarity effect occurs; other things being equal, the breakdown voltage at a positive tip is significantly lower than at a negative tip. Various mechanisms have been proposed to explain this effect [1,2]. The work [2] considers a two-stage process associated with the capture of electrons by traps. When the teen polarity is positive, the main source of ionization can be the Zener-type tunneling effect [2,3]. It can be of predominant importance under conditions of very high electric field strength in the vicinity of the point (short-term processes are characterized by a strength of the order of 109 V/m). For an engineering description of the main characteristics of a pulsed breakdown under conditions of a highly inhomogeneous field, the urgent task is to adapt existing physical models to calculation conditions with an acceptable level of computational resources. In this case, it is necessary to quantitatively correspond the results obtained to the experimental data at the level of accuracy of the experimental data. In the work [4] a model of field ionization of dielectric macromolecules is proposed, taking into account the Debye screening effect. The accumulation of positive charge carriers reduces the ionization potential of molecules, which leads to a sharp acceleration of discharge development when a critical hole concentration is reached. In a nonuniform field, a threshold jump in the rate of generation of charge carriers can be considered as a phase transition leading to the formation of an ionization wave [5]. Taking into account the above, one can use this model to describe the pulsed breakdown of a polymer dielectric in the „positive point-plane geometry“, when the delay time of the breakdown is determined by the speed of the ionization front in the streamer head. The ease of implementation of this model and the small number of parameters included in it make it possible, on its basis, to develop an engineering method for describing the volt-second characteristics (VSCs) of polymer dielectrics, which does not require significant computational costs when solving a specific problem.

1. Description of the calculation model

The model of pulsed breakdown of polymer dielectrics, proposed in works [4,6,7], allows for a relatively simple implementation in finite element modeling systems, such as ANSYS or COMSOL Multiphysics. In this case, it is necessary to set the basic parameters specific to this material. The rate of increase in the concentration of carriers is determined by the transparency of the potential barrier $D_{HL} = \exp(-\frac{4\sqrt{2m}}{3e\hbar} \cdot \frac{\Delta^{3/2}}{E})$, depending on the local strength value electric field E and potential barrier height Δ. The latter value is calculated taking into account its reduction ΔI due to Debye screening $\Delta = E_g - \Delta I(p)$, where E_g — energy gap width, p — charge carrier concentration. In this case, the width of the energy gap is understood as $E_g = |E\text{HOMO} - E\text{LUMO}$ where E HOMO and E — energies of the HOMO and LUMO levels during the tunneling transition of an electron from the level of the highest occupied orbital of a macromolecule (HOMO) to the lowest unoccupied orbital (LUMO) of a neighboring molecule. The tunnel ionization rate constant $k_{HL}(p)$ is given by the formula $k_{HL}(p) = \nu_0 D_{HL}$.

The rate of accumulation of charge carriers, neglecting recombination, is determined by solving the differential equation $\frac{dp}{dt} = k_{HL}(p) \cdot (M0 - p)$ — the initial concentration of fragments of macromolecules capable of ionization $10^{27}\,\mathrm{m}^{-3}$. Substituting the formula for the transparency of the potential barrier into the last expression makes it possible to explicitly obtain the dependence of the generation rate of charge carriers on their concentration and electric field strength:

$$\frac{dp}{dt} = \nu_0 \exp\left(-\frac{4\sqrt{2m}}{3e\hbar} \times \frac{\left(E_g - e^2 \cdot \left(4\pi\varepsilon_0 \cdot \sqrt{\varepsilon_0 kT/\varepsilon^2 p}\right)^{-1}\right)^{3/2}}{E}\right)(M0 - p). \tag{1}$$

The process of loss of insulating properties is considered complete when the charge carrier concentration reaches $p_{\mathrm{cr}} \sim 2 \cdot 10^{23}\,\mathrm{m}^{-3}$ [7].

The value of the frequency factor included in formula (1), according to the authors of the model, is $\nu_0 \sim 10^{16}\,\mathrm{s}^{-1}$ and can be interpreted as the frequency of collisions of an electron with a barrier. At the same time, the calculations carried out by the authors demonstrate a very significant difference between the experimental and calculated dependence of the breakdown time on the rate of voltage rise. It is obvious that in real dielectrics the distribution of energy potentials, due to the presence of defects, can differ significantly from that characteristic of an ideal dielectric. The experimentally obtained dependences of the pulsed electric strength on the duration of application of the time current characteristic (DoRE) of real dielectrics make it possible to select the parameters of the field ionization model $\nu_0$and E_g, which retains the predictive capabilities of describing the process of electrical breakdown in various temporal and spatial modes of exposure to a strong electric field [8]. The choice of the value of the frequency factor ν_0 corresponding to the experimental data can be commented on as follows. At a field strength significantly higher than the static breakdown strength, the transparency of the potential barrier D_{HL} should be of the order of unity. In this case, in accordance with formula (1) $\frac{dp}{dt} \approx \frac{p_{\mathrm{cr}}}{\tau} \approx \nu_0 \cdot M0$, where$\tau$ — breakdown time. Extrapolation of experimental data [7] for PET to the region of electric fields $E > 10^9\,\mathrm{V/m}$ leads to the estimated value of $\tau \approx 10^{-12}\,\mathrm{s}$ and, accordingly, the frequency factor $\nu_0 \sim 10^9\,\mathrm{s}^{-1}$. Further calculations confirm the qualitative agreement of this estimate with the experimental results. Such a significant deviation of the frequency factor value from the original theoretical value will be discussed below.

During a nanosecond breakdown, the drift velocity of charge carriers is significantly lower than the speed of the ionization wave [5] taking into account the fact that the mobility of holes, according to known estimates, $\mu \sim 10^{-8}\,\mathrm{m}^2/(\mathrm{V{\cdot}s})$ [9]. Neglecting drift allows you to integrate this model into a field problem COMSOL Multiphysics using the ordinary differential equation (ODE) physics interface. This greatly reduces the requirements for computing resources and makes the solution to the problem quite stable.

The solution in the axisymmetric $2D$ model is achieved relatively simply in a field geometry close to uniform, and makes it possible to select the model parameters ν_0 and E_g taking into account experimental data [8]. However, when describing experiments with an inhomogeneous field (pit — plate), a difficulty arises in that the use of the axisymmetric $2D$ model leads to instability of calculations associated with a possible random deviation of the streamer trajectory from a rectilinear one. In this case, the streamer channel, from the point of view of the axisymmetric model, turns into a hollow tube, which is accompanied by a sharp drop in the field strength in its head and a stop of movement, which has no real physical meaning. Problems of this kind are solved in some works by introducing artificial diffusion [10], which makes the calculation results less convincing. The use of $3D$ models leads to very large computational difficulties that are unacceptable for engineering calculations. Nevertheless, $3D$ modeling can be very useful for identifying individual patterns characteristic of nanosecond breakdown of dielectrics.

2. Results of numerical calculations in a field close to uniform

Calculations of the breakdown of PET in the electrode geometry corresponding to a uniform field for a linearly increasing voltage were carried out in accordance with the experimental conditions of the work [7]. The purpose of the calculations was to select the model coefficients $\nu_0$and E_g in accordance with the experimental VSC. The breakdown criterion was the achievement of a critical concentration of charge carriers along the entire length of the line connecting the electrodes. As follows from the experimental data [2,11], the breakdown in a field that is initially close to uniform is of a streamer nature, which is not taken into account in the two-dimensional calculations performed. However, it can be assumed that the streamer stage in this geometry is relatively short in time compared to the time of accumulation of charge carriers in the volume of the interelectrode space, since the streamer propagates in a pre-ionized medium.

The selected values of $\nu_0 = 4.2 \cdot 10^9\,\mathrm{s}^{-1}$ and $E_g = 3.9\,\mathrm{eV}$ are somewhat different from previously published [8], which is due to a more strict account of the geometry of the electrodes and the structure of the electric field in the COMSOL model compared to the one-dimensional calculation. The VSC obtained from the calculation data

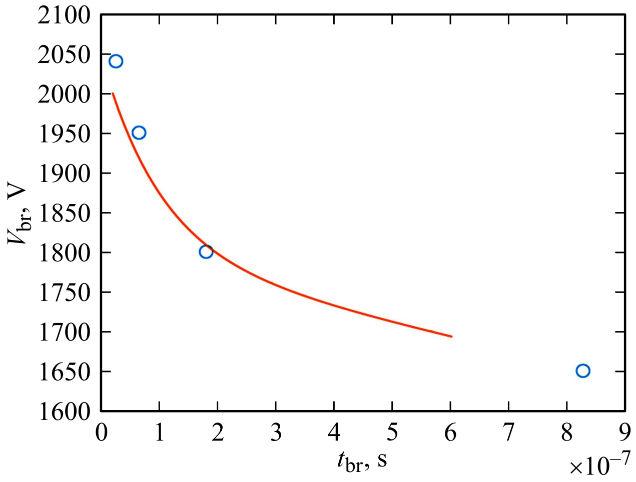

Figure 1. Results of modeling the HCV breakdown of a polyethylene terephthalate film (solid curve), experimental data from the work [7] (○).

(Fig. 1) well describes the experimental data in the time range 10–1000 ns.

The physical meaning of the model parameters ν_0 and E_g and their difference from theoretical values in relation to experimental conditions will be discussed below.

3. Main results of numerical modeling in geometry „point–plane“

An estimated calculation of the VSC of the discharge gap in the formulation we have adopted involves the formulation of several basic relationships, constructed both on the basis of generally accepted formulas and on the use of certain assumptions related to the geometry and ionization model used.

The task of the calculation is to obtain data on the main characteristics of the breakdown of a dielectric in a model configuration to clarify the patterns connecting the radius and speed of the streamer with the geometry of the discharge gap and the parameters of the voltage pulse. In this case, we are not talking about modeling the conditions of a specific experiment, although the main features of the class of experiments under consideration are preserved: high strengths and a highly inhomogeneous field. Taking into account the task at hand, the test geometry of the computational domain was selected based on the results of trial calculations to obtain a sufficiently high spatial resolution of the grid with satisfactory convergence and unambiguity of the calculation results.

A description of the finite element model calculation of streamer dynamics in the „point— plane“ geometry is given in the Appendix An assessment of the impact of the adopted simplifications on the result is also given there.

In contrast to the published COMSOL models, which use the plasma [12] module to calculate the propagation of a streamer in a gaseous medium, the modeling was carried out in a simplified formulation, using the physical interfaces of ordinary differential equations (ODE) and Electric Currents. In accordance with the above, the movement of the medium was not considered The concentration of charge carriers was determined in the ODE module, and the potential distribution in the volume was determined in the Electric Currents module. The conductivity of the medium in the ionization zone was determined taking into account the concentration and mobility of carriers. When a critical carrier concentration was reached, the conductivity of the medium was artificially increased to a given value, which was a variable parameter.

The parameters of the PET field ionization model, selected by simulating breakdown in a uniform field, were used.

This formulation makes it possible to dramatically reduce the complexity of the calculation and implement it in the 3*D* formulation without overcoming significant computational difficulties. Based on the results of numerical simulation in the test configuration, the following conclusions can be drawn:

a) comparison of the calculation results for different conductivities of the streamer channel shows a rather weak dependence of the speed of propagation of the ionization region on the conductivity. For the model calculation, when the conductivity changes from 5 to 100 S/m, the average speed of the streamer head changes from $5\cdot 10^4$ to $1.2\cdot 10^5$ m/s;

b) the radius of the streamer head remains practically unchanged and, under the conditions of the model calculation, is of the order of 1 μm;

c) the characteristic radial size of the ionization region is close to half the radius of the streamer channel, longitudinal — (0.1–0.2), which does not contradict the available results of more detailed calculations of the streamer parameters [13,14].

4. Estimated ratios for VSCc

Determining the radius of the streamer is a key point for evaluating VSC calculations in the nanosecond region. At the same time, there is no single approach to solving this issue [14,15].

In the context of the problem at hand, the following considerations can be applied to obtain a simple estimate of the expected streamer radius. Based on the principle of current continuity, it is possible to compare its components according to sections of the discharge circuit.

In the area in front of the streamer, a capacitive current i_c, formed by moving the streamer head at a speed of u_{str} at a constant voltage V.

$$i_c = V\frac{dC}{dt} = V\frac{dC}{dx}\cdot\frac{dx}{dt} = V\frac{dC}{dx}u_{str}, \qquad (2)$$

where C — streamer capacity.

The speed of streamer propagation in accordance with [5] can be estimated as

$$u_{str} \approx \frac{w}{\Delta p}\delta_E, \tag{3}$$

where δ_E — the characteristic size of the field inhomogeneity region in which ionization occurs, Δp — the change in the concentration of charge carriers, w — the rate of generation of charge carriers (the designation from the cited work is retained here, in terms of this work $w \equiv \frac{dp}{dt}$). Then $\frac{w}{\Delta p} \approx \frac{1}{t_{\mathrm{cr}}}$. Taking the value δ_E equal to the longitudinal size of the ionization zone h_i, we obtain

$$u_{str} \approx \frac{h_i}{t_{\mathrm{cr}}}. \tag{4}$$

The charge q_c transferred through the circuit during the time t_{cr}, will be

$$q_c = i_c t_{\mathrm{cr}} \approx V\frac{dC}{dx}h_i. \tag{5}$$

The charge q_g generated during the time t_{cr} in the ionization region can be estimated as the product of the charge density ep_{cr} by the volume of the layer with thickness h_i and the radius of the ionization zone r_i:

$$q_g = ep_{\mathrm{cr}}\pi r_i^2 h_i. \tag{6}$$

Based on the assumption of a constant charge in the streamer head, we obtain the relation for determining the radius of the ionization zone r_i:

$$V\frac{dC}{dx} \approx ep_{\mathrm{cr}}\pi r_i^2. \tag{7}$$

Hence

$$r_i \approx \sqrt{\frac{V\frac{dC}{dx}}{\pi e p_{\mathrm{cr}}}}. \tag{8}$$

In accordance with the numerical calculation data, the radius of the streamer is approximately twice as large:

$$r_{str} \approx 2\sqrt{\frac{V\frac{dC}{dx}}{\pi e p_{cr}}}. \tag{9}$$

Since the derivative dC/dx included in (9) is a function of the desired radius, its unambiguous determination can be obtained by jointly solving equation (9) and the equation that determines the dependence of dC/dx on the radius of the streamer, its length and the interelectrode distance. This dependence can be obtained using the formula [16]:

$$C = \frac{2\pi\varepsilon l}{\ln\frac{l}{r_{str}} - D}, \tag{10}$$

where the parameter D depends on the ratio h/l (Fig. 2). A more accurate result can be obtained by numerically solving the electrostatic problem, in which the geometry of the computational domain of the previous section is used, and the streamer is modeled by a cylindrical rod with a radius of curvature r_{str}. Solving equation (9) using the $dC/dx(r_s tr, h, l)$ dependence allows us to obtain the radius value for a given voltage and geometry of the discharge gap. The radius value obtained by the above method agrees well with the data from numerical simulation of streamer development in the test geometry.

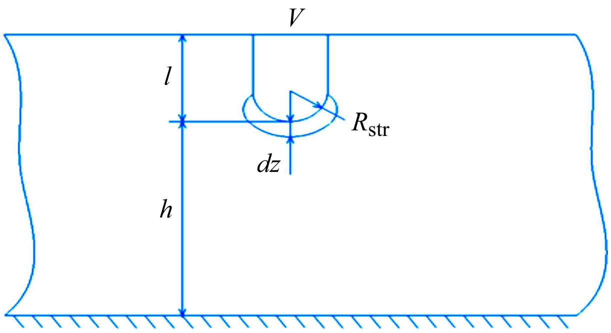

Figure 2. On determining the radius of the streamer.

Estimation of the streamer propagation speed is based on calculating the time t_{cr} under reach the critical value of the hole concentration $p_{\mathrm{cr}} = 2 \cdot 10^{23}\,\mathrm{m}^{-3}$ depending on the field strength E. The time t_{cr} was determined by integrating equation (1) using the standard Matlab ode45 procedure. The obtained $t_{\mathrm{cr}}(E)$ dependences for the PET and PMMA are shown in Fig. 3. According to them, a significant slowdown in the ionization process is observed at voltage values close to static breakdown At a strength of the order of $2 \cdot 10^9$ V/m, the critical time for PET is $t_{\mathrm{cr}} \sim 10^{-11}$ s, while the parameters of the field ionization model from the work [7] lead to unrealistically small values of $t_{\mathrm{cr}} \sim 10^{-14}$ s.

The parameters of the PMMA model for breakdown in a uniform field were selected based on limited data [17] and were adjusted in accordance with [18] to improve the fit of the entire set of experimental data (see Section 5). The experimental VSCs of PMMA used are satisfactorily described at $\nu_0 = 8 \cdot 10^8\,\mathrm{s}^{-1}$ and $E_g = 2.37\,\mathrm{eV}$.

The field strength in the streamer head required to determine t_{cr} is calculated using the formula (11) [18] taking into account the correction for the decrease in strength due to the finite thickness of the ionization zone $\eta \sim 0.8$ [14]:

$$E = \frac{2V\eta}{r_{str}\ln(\frac{2h}{r_{str}})}. \tag{11}$$

Thus, the procedure for estimating breakdown parameters in a given geometry at a given voltage is reduced to the following steps:

1) $dC/dx(r_s tr, h, l)$ is calculated for the given h and l for the set of values r_{str}. The average value over all positions of the streamer head is a function of the radius $dC/dx = f(r_{str})$ (7);

2) Solving (9) and (10) together, we obtain the value r_{str};

3) using formula (11) we determine the field strength in the streamer head;

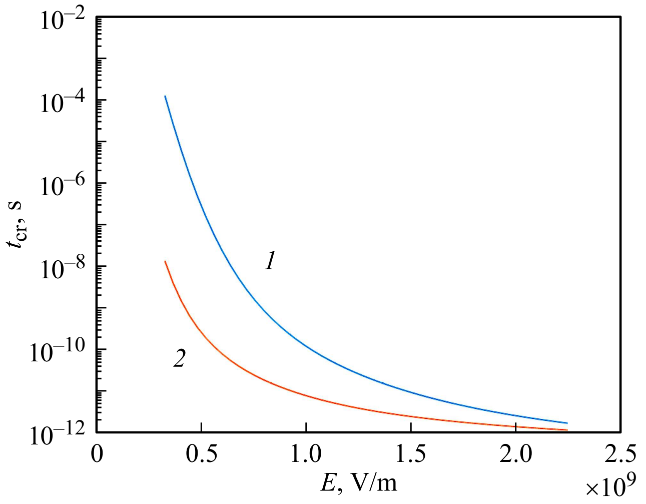

Figure 3. Relationship between field strength E and t_{cr} for the PET (*1* PMMA*2*) model.

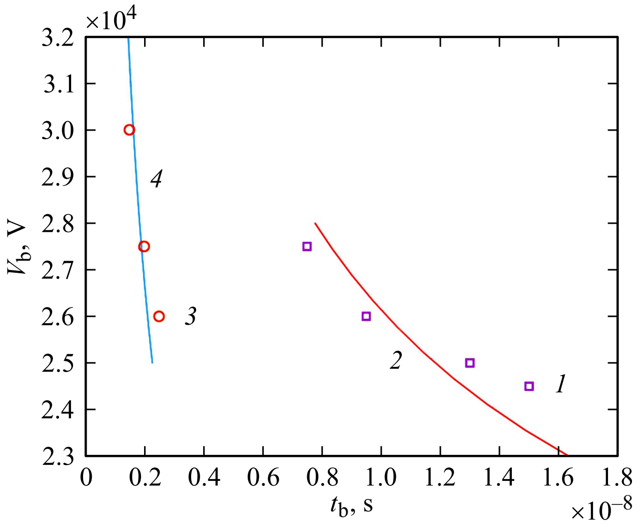

Figure 4. Experimental (*1*) and calculated (*2*) VSCs for PET with a thickness of 480 μm and for PMMA (with a thickness of 400 μm (respectively (*3*) and (*4*)) in geometry „point — plane“ according to the results of the evaluation calculation.

4) determine the corresponding value t_{cr} in accordance with the dependence of Fig. 3;

5) Using formula (4), we calculate the speed of the streamer, and, further, the breakdown time in accordance with the length of the interelectrode gap.

5. Comparison of estimates with experimental data

To check the applicability of the above approach to the description of experimental data on the breakdown of solid dielectrics, let us evaluate the type of VSC of PET according to the data for PET and PMMA (Fig. 4).

The streamer radius, estimated using formulas (9), (10), is from 6 to 7 μm for the corresponding experimental geometries The results of the estimated calculation of the VSC of the gap „point — plane“ are in qualitative agreement with the data of the work [19]. Taking into account the significant scatter of experimental data and the approximate nature of the calculation, the correspondence can be considered satisfactory.

6. Discussion

When comparing calculations based on the field ionization model with the results of experiments by different authors, the question arises about the significant difference in the value of the frequency factor $\nu_0 \sim 10^8 - 10^9\,\text{s}^{-1}$ from theoretical estimates. Thus, when using the value $\nu_{0\text{theor}} \sim 10^{16}\,\text{s}^{-1}$, the dependence of the breakdown voltage on time is practically absent under the conditions of all the cited experiments, which contradicts the experimental data.

The following qualitative explanation can be offered for the difference between the theoretical values and those selected in accordance with the experiment. Due to the extremely strong dependence of the transparency of the potential barrier on the strength of the external electric field, in a real inhomogeneous dielectric, an intense process of field ionization when a field is applied can begin for a limited part of the dielectric molecules. This can be facilitated by structural defects or the presence of impurities that lower the ionization threshold. Accordingly, the ionization rate can be estimated as $dp/dt \sim \nu_{0\text{theor}} D_{HL}(M_{eq} - p)$, where $M_{eq} \ll M_o$ — the number of macromolecules corresponding to a group of particles with a reduced ionization threshold. Taking into account the fact that in all modes under consideration $p \ll M_o$,one can approximately estimate the ratio of the frequency factor used in calculations and the theoretical values as $\frac{\nu_0}{\nu_{0\text{theor}}} \sim \frac{M_{eq}}{M_0}$.

This assumption correlates at a qualitative level with the relationship between the value $E_g = 3.9\,\text{eV}$ obtained in describing the experimental results for PET and the energy gap width 6 eV given by the authors [7].

It can also be assumed that there is a mechanism for changing not only the height, but also the width of the potential barrier in the electric field [20]. Taking this factor into account in the future may lead to a more rigorous description of the pulsed breakdown of polymer dielectrics.

Regarding the simplifications adopted in the evaluation model, the following can be said.

When calculating the critical generation time of charge carriers, their relaxation associated with the conductivity of the medium was not taken into account. The conductivity of the plasma in the streamer head, according to the work estimate [5], can be calculated as $\sigma_0 \cong (e\varepsilon\varepsilon_0\mu w)^{1/2}$, where w — the rate of generation of charge carriers. From Fig. 4, *b* it is clear that the rate of generation of charge carriers at the ionization front is about $5 \cdot 10^{34}\,\text{s}^{-1}$. Using this value we get $\sigma_0 \sim 0.05\,\mathrm{S/m}$. Accordingly, the Maxwell relaxation time$\tau_M \approx \frac{\varepsilon\varepsilon_0}{\sigma}$ is of the order of $5 \cdot 10^{-10}\,\mathrm{s}$, which is an order of magnitude greater than the critical time for the cases considered Not taking charge relaxation into account limits the use of the model to the range of breakdown times $\tau < \frac{h}{r_{str}}\tau_M \sim 50\,\mathrm{ns}$ [11].

When estimating the field strength of the streamer head, the influence of the space charge in the carrier generation region was not taken into account. Unlike a discharge in a gaseous medium, where this influence is decisive, within the framework of the field ionization model, the transition of the medium to a highly conductive state occurs abruptly when the critical density of charge carriers is reached. The numerical solution of the electrostatic problem in the geometry corresponding to the above calculations, with the introduction of a space charge with density ep_{cr} into the generation region (this estimate is overestimated) demonstrates an increase in the field strength by approximately 10% compared to the case of neglecting the space charge. Thus, this simplification in the formulation used does not lead to critical errors in the results obtained.

In the estimation calculations, the influence of the streamer channel conductivity was not taken into account. From model numerical calculations it is clear that the streamer speed increases quite slightly with increasing conductivity (see (4)). As the streamer moves, the growing resistance of the channel should lead to a drop in voltage at its head and, as a result, a decrease in speed. A possible explanation for the small influence of this factor is the compensating effect of an increase in tension with a decrease in radius, which, as follows from formula (2), is associated with a decrease in tension. Therefore, the uncertainty in the channel conductivity does not significantly affect the estimated breakdown times.

Conclusion

Based on the implementation of the field ionization model in the COMSOL finite element environment, the parameters E_g and ν_0 of dielectrics were selected that satisfactorily describe the SSCs corresponding to breakdown in a uniform field.

Using these parameters, three-dimensional model calculations were carried out in the point — plane configuration in order to identify qualitative patterns of breakdown, which are difficult to obtain from experimental results.

Simplifications based on the results of model calculations make it possible to propose a method for estimating the main breakdown parameters, based on determining the characteristic generation time of charge carriers.

A formula is proposed for determining the radius of the streamer, based on the charge balance of the system.

The speed of the streamer is determined based on the critical time for the formation of a space charge in the region of its head and the size of the ionization region.

The results of estimated calculations of the breakdown stress characteristics of PET and PMMA „in the point — plane geometry“ are in satisfactory agreement with the experimental data.

Appendix

Finite element calculation in geometry „point–plane“

A brief description of the finite element calculation of PET film breakdown in the COMSOL Multiphysics environment in the „point — plane“ geometry in the $3D$-formulation. The computational domain was a 45-degree cylindrical sector, on the side faces of which the condition that the normal component of the current is equal to zero is set (Fig. 5). The tip is made in the form of an ellipsoid with a radius of curvature of $3\,\mu\mathrm{m}$. Distance between electrodes $d = 22.5\,\mu\mathrm{m}$. To the tip a voltage pulse close to rectangular was applied, with an amplitude$U_m = 10\,\mathrm{kV}$ with a time constant of exponential rise of the front of $0.1\,\mathrm{ns}$.

The simulation was carried out in a simplified formulation using ordinary differential equations (ODE) and Electric Currents physics interfaces. The effect of the space charge of the streamer head on the field strength is not taken into account. For information on how much this assumption affects the integral characteristics of the process, see below. It should also be noted that when simulating a breakdown, the conductivity of the plasma formed as a result of the motion of the streamer cannot be calculated within the framework of the field ionization model. Thus, another problem arises related to determining the plasma conductivity of the streamer channel and the degree of its influence on the characteristics of the process. In the calculation, the results of which are presented below, the conductivity value was taken equal to $10^2\,\mathrm{S/m}$. This choice is based on the following rough estimate. According to the data [21], the mobility of carriers in the breakdown channel is of the

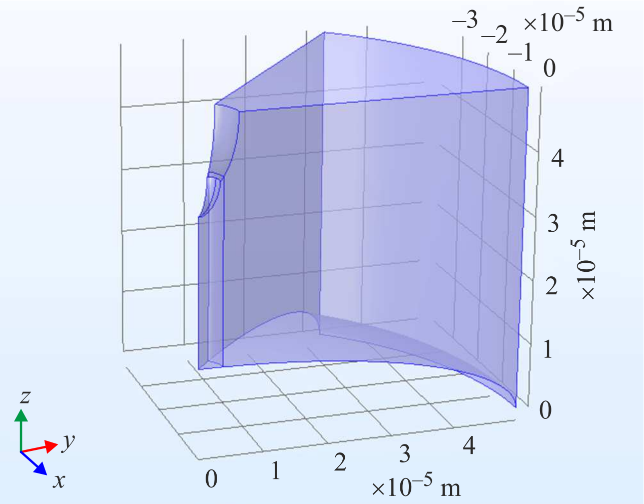

Figure 5. Geometry of the computational domain.

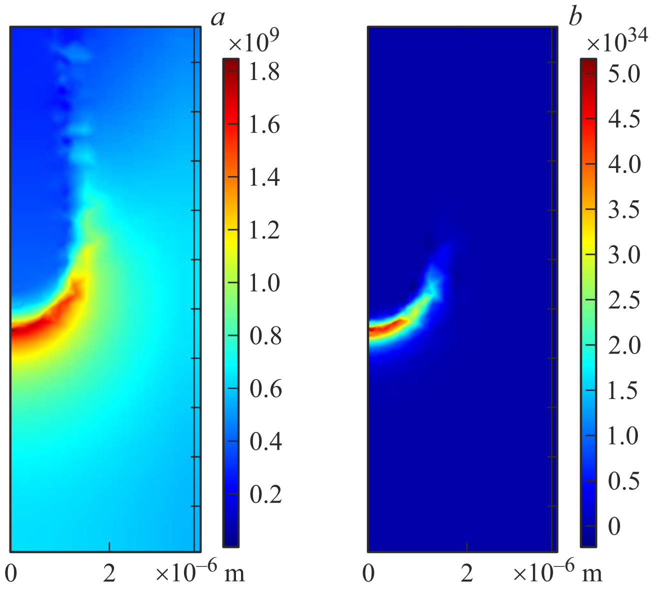

Figure 6. An example of the spatial distribution of the field strength (*a*) and the rate of generation of charge carriers in the vicinity of the streamer head (*b*).

order of $\mu_k = 10^{-6}\,\mathrm{m}^2/(\mathrm{V{\cdot}s})$. Taking this into account, the conductivity value presented above is obtained under the condition that the density of the material in the channel is close to the density of the solid body, and the material is completely ionized $\sigma = \mu_k M0e$. To determine how sensitive the results are to the conductivity value, calculations were carried out with variations in this parameter. The results demonstrate a rather weak dependence of the propagation speed of the ionization region on conductivity. When the conductivity changes from 5 to 100 S/m, the average speed of the streamer head changes from $5 \cdot 10^4$ to $1.2 \cdot 10^5$ m/s.

Although at the initial stage of calculations, as a rule, several branching channels are formed, in all calculation options it is possible to identify the main, fastest-propagating channel of the streamer, for which the main parameters can be obtained with a certain degree of accuracy: radius, propagation speed, field strength in the streamer head .

Fig. 6 shows an example of the spatial distribution of the field strength and the rate of generation of charge carriers in the vicinity of the streamer head. The radial size of the region in which the majority of charge carriers are generated is approximately half the radius of the streamer, the longitudinal size is — (0.1−0.2).

The degree of influence of the field strength created by the uncompensated space charge in the streamer head can be estimated from the critical concentration of carriers and the size of the region of their generation. The numerical solution of the electrostatic problem in the geometry corresponding to the above calculations with the introduction of a space charge with density epcr into the generation region (this estimate is overestimated) demonstrates an increase in the field strength by approximately 10% compared to the case of neglecting the space charge. Thus, this simplification does not lead to critical errors in the results obtained.

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Conflict of interest

The authors declare that they have no conflict of interest.

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