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Original Article

Theoretical Foundations of Fractality of Electric Breakdown Discharge in Diodes

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Abstract — *The article presents the theoretical foundations for describing the processes that determine the fractal nature of the breakdown of dielectrics, during which an electric charge flows through a fractal tree from one electrode to the second. To construct a phenomenological theory for describing the process of branching of a fractal tree, a model for describing the motion of a flow uncompensated in charge between two electrodes with equal potentials is considered. It is proved in this work that, at threshold values of the discharge parameters, a Pierce instability arises, which at the nonlinear stage leads to "blocking" of the flow and, thereby, to the appearance of a scattering center. In general, this is scattering in the transverse direction. In the mode with the formation of narrow channels of current propagation, the spread in the transverse direction does not occur symmetrically but with the branching of the current channels. The branching process has a probabilistic nature, in particular, in the direction of the newly created branches and, therefore, the dielectric breakdown is a process of random growth of branches of a fractal discharge tree. The article mathematically (10) confirms that the discharge reaches a quasi-stationary state. The current flowing through the first current channels at one electrode is distributed over many branches of the channel tree at the second electrode.*

On the basis of the developed models of the discharge, it is possible to develop recommendations both on the possibility of preventing the occurrence of a discharge in diodes and on the development of a controlled discharge of the discharge in any dielectric structures of radio engineering and electronic devices.

Keywords — *Fractal discharge, Laminar stage, Space charge, Current channel, Dielectric, Diode.*

I. INTRODUCTION

At present, a huge amount of experimental material and data have been accumulated on the numerical simulation of the electric strength of dielectrics (see, for example, [1-6,13,18-20]). It was possible to register the appearance of plasma channels and the structure of the glow during the breakdown of dielectrics.

It follows from the results of a number of experimental works (see, for example, [1, 2, 13]) that the process of electric discharge (breakdown) in dielectrics has a pronounced structure of a fractal tree. Therefore, the use of concepts associated with the concept of "fractal" introduced by B. Mandelbrot [7] is adequate to the experimental situation. The fractality of electrical breakdown or discharge is also observed in computer simulations [9]. However, there is no clear presentation of the mechanisms of formation of this fractal tree.

The results of experiments and computer simulation determine the phenomenological level of ideas about the breakdown in a dielectric, on the basis of which its phenomenological theory can be built. In this article, let's present a physical model of the process that leads to the fractal nature of the discharge in dielectrics.

The considered discharge process is the process of electric charge flow from one electrode to the second along a complex branched set of channels, constituting a fractal tree. The process of electric charge flow is reduced to the alternation of the following stages:

- laminar stage, during which the channel of the fractal tree thickens and lengthens in an evolutionary manner;
- stage of specific instability of the electric charge flow and the process of branching of a fractal tree;
- stable mode of charge flow (similar to the mode for a flat diode).

The discharge branching process occurs at the discharge front, where the force destroying the flow acts in the transverse direction due to the space charge. To construct a phenomenological theory of the branching process, let's consider a model system: the motion of a flow uncompensated in charge between two electrodes with equal potentials

II. MATERIALS AND METHODS

A. Effect of discharge of excess charge in a flow of charged particles

It is known [7-12,15] that in a one-dimensional electron flow passing through a planar diode, stationary states are possible both through the passage of particles (I) and with the reflection of a part of electrons from a virtual cathode (II). In this case, there is a hysteresis of states. In [7-12], the boundaries of each mode are determined (see, for example, [10]), and the possibility of transitions between them is shown. The presence of transitions is confirmed both by experiment [15, 18] and by the very practice of operation of electron tubes [16]. The stability of the flux in a diode is investigated in [15].

States I and II differ in a number of parameters. In particular, the number of electrons in the flow in state II is greater than in-state I. Therefore, the II→I transition is accompanied by the discharge of excess charge [12, 15]. As a result, a short (on the order of the time of electron flight through the diode) current pulse with an amplitude of the order of the injection current appears at the exit from the diode against the background of the injection current. Experiments confirming the presence of the reset effect are carried out in [15, 18, 19].

In a transversely limited electric flow passing between two conducting planes, stationary states are possible both with a longitudinal flight of particles and with a scatter of flow particles by a volume electric field when the parameters of the charge propagation channel change, transitions between states are possible.

The states differ in a number of parameters. In particular, the transition from the first state to the second occurs when a certain value of the channel length is reached. Channel elongation in the first state is accompanied by the accumulation of space charge.

At threshold values of the parameters, instability of the Pierce instability arises [12], which at the nonlinear stage leads to "blocking" of the flow and, thereby, to the appearance of a scattering center.

Let's analyze the stationary states of the electron flow in connection with the effect of accumulation and charge spread.

B. State with longitudinal passage of particles

Let's assume that a cylindrical electron flux of radius R limited in the transverse direction is injected along z in the space between the flat electrodes $z_1 = 0$ and $z_2 = L$. The density of electrons at the input, z = 0, is equal n_0, and the speed u_0. The thermal spread is assumed to be small $v_T << u_0$. The potentials of the electrodes are the same.

In the regime with a longitudinal flight of electrons, the flow is described by the system of hydrodynamic equations

$$\partial u/\partial t + u\,\partial u/\partial z = \partial\varphi/\partial z \tag{1}$$

$$\partial n/\partial t + \partial(nu)/\partial z = 0 \tag{2}$$

$$\Delta\varphi = \alpha n \tag{3}$$

For speed, density and potential, dimensioned by quantities u_0, n_0 and mu_0^2. Coordinate is dimensioned by L time is L/u_0. The parameter is determined by the formula

$$\alpha = \omega_K^2 L^2/u_0^2,\ \omega_p^2 = 4\pi e^2 n_0/m. \tag{4}$$

For the stationary case, system (1) - (3) has a solution

$$u = (2\beta)^{1/2},\ n = (2\beta)^{-1/2},\ \varphi = \beta \tag{5}$$

where β is found from the equation

$$\partial^2\beta/\partial z^2 + \Delta_\perp\beta = \alpha(2\beta)^{-1/2} \tag{6}$$

The second term on the left-hand side describes the weakening of the longitudinal field due to its three-dimensional distribution. In the first state, this term does not qualitatively change the result. Therefore, β is found from the equation

$$\begin{aligned} &\beta = \eta^2/2, \\ &(z-1/2)\,sign(z-1/2)\,g\,(a/2)^{1/2} = \\ &= (\eta-\eta_a)^{3/2}/3 + \eta_a(\eta-\eta_a)^{1/2}, \end{aligned} \tag{7}$$

η_a from the equation

where g – the coefficient is of the order of unity. It follows from (8) that the first state becomes unstable at

$$.\alpha = 8/9\,g^2 \tag{8}$$

C. Spread of space charge

Two fields act on the charges moving between the electrodes. Firstly, longitudinal, directed from one electrode to the second. It is this field that defines just the first state. Second, the space charge field, which repulses the charges in the transverse direction, has a strong effect. When the length of the current channel increases to a certain value (see condition (9)), the first state becomes unstable, and a qualitative change in the particle trajectories occurs. In a one-dimensional approximation, in this case, reflection from the virtual cathode would occur. However, reflection in the three-dimensional case in the absence of an external magnetic field and small transverse dimensions of the channel is not a common case. In general, this is scattering in the transverse direction. When the transverse dimensions of the current propagation channel are smaller than their longitudinal dimensions, the scatter of the space charge by the three-dimensional field occurs in the transverse direction. The spread can't be symmetrical if the charge propagates in the form of relatively narrow channels. In the mode with the formation of narrow channels of current propagation, the spread in the transverse direction does not occur symmetrically but with the branching of the current channels. The process of charge spread during channel branching reduces the space-charge field. It is possible to say that as the channel length increases to a certain length, it becomes energetically favorable for the channel to branch out.

The branching process has a probabilistic nature, in particular, in the direction of new branches. Therefore, dielectric breakdown is an example of the process of random growth of fractal branches.

D. Stability of current propagation channels

Let's consider the stability of current propagation channels since it is known that particle fluxes under certain conditions can be unstable. So, in [20-21], the stability of the electron flux compensated by a positive charge is studied; in [19], the electron flux during injection into a semi-bounded space is considered, in [14] and [18] the equation of the oscillation spectrum for fluxes without particle reflection is obtained.

The branches of a quasi-stationary discharge tree could be unstable with respect to Pierce perturbations if the parameter is greater than a certain value. However, branches propagate like this when a tree is formed that this parameter remains below the Pierce instability threshold.

III. RESULTS AND DISCUSSION

At each stage of propagation of current propagation channels, this process occurs in a similar way with certain properties of self-similarity (the structure of tree branches coincides with the structure of the tree itself), which leads to the formation of a fractal tree with the property of self-similarity.

The structure of the discharge can be characterized by a fractal dimension. The fractal dimension D is measured by counting the number of branches N (R) contained in a sphere of radius R: $N(R)=R^D$. This implies that the fractal dimension is related to the structure of the tree. Moreover, the density of branches $\rho(r)$ satisfies the law of similarity $\rho(r)\approx r^{-(d-D)}$, where d – dimension of the space in which the fractal is located.

Thus, the fractal dimension depends on the physical properties of the dielectric breakdown process and, therefore, is a numerical characteristic of the physical breakdown processes. It determines the similarity coefficient of the distribution of the total charge of the flow on the fractal. When the discharge reaches a quasi-stationary state, the current flowing through the first current channels at one electrode is distributed over many branches of the channel tree at the second electrode:

$$\sum_{k=1}^{N_1} n_{1k} v_{1k} S_{1k} = \sum_{k=1}^{N_2} n_{2k} v_{2k} S_{2k} \qquad (10)$$

Here n_i, v_i – density and speed of charges in the channel, S_i – channel cross-section, and N_i – number of channels at the i-th electrode.

IV. CONCLUSION

Thus, the paper presents the theoretical foundations for describing the processes that determine the fractal nature of the breakdown of dielectrics, during which an electric charge flows through a fractal tree from one electrode to the second. The process of complicating the structure of the branches of a fractal tree is qualitatively considered. The existing regime with the longitudinal passage of charges ensures the elongation of the branches of the fractal tree. It is shown that the branching thresholds are determined by the achievement of the conditions for the occurrence of a Pierce instability, which leads to the formation of a scattering center, flux scatters in the transverse direction, branching of a fractal tree with a simultaneous discharge of excess space charge.

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