Computer Simulation of Electrothermal Instability Development and Channel Formation of Solid Dielectric Thermal Breakdown

A.A. Cheglokov, V.V. Lopatin*, M.D. Noskov

Seversk State Technological Academy, Kommunisticheskij av. 65, Seversk Tomsk reg., 636036, Russia, +7(3823)546426, E-mail: cheglok@ssti.ru

** Research Institute of High Voltages, Lenina av., 2a, 634050, Tomsk, Russia*

Abstract – The physical-mathematical model of temperature, electric field, charge density distributions and phase transition dynamics in the course of thermal breakdown is considered. The model has been deployed to describe eletrothermal instability development and breakdown channel formation. Computer simulation method has been used to investigate the discharge channel propagation which is associated with the growth of the highly conducting state region into the insulator. The fields dynamics is calculated on the base of finite-difference approximations within cubic lattice. The results of computer simulation of the conducting channel formation in needle-plane electrode geometry under dc voltage in BeO ceramic are presented. The effects of conduction inhomogeneities on the channel propagation are discussed.

1. Introduction

The propagation of conducting discharge channels is accompanied by the dielectric material transition into the conducting plasma state. That can be a result of development of ionization, electromechanical, electrothermal instabilities. The electric field, charge, and energy dynamics within the discharge channel and dielectric material govern all these instabilities. In the present paper we consider the discharge channels propagation due to electrothermal instability.

Electrothermal breakdown takes place, when the Joule heating by the conduction current exceeds the dissipation into the surrounding medium at least in local region of the insulation [1,2]. If the conductivity of insulation increases strongly with the temperature, thermal breakdown may be followed by the development of electrothermal instability. In this case the positive feedback between the increase of conductivity and the power of Joule heating results in acceleration of the heating and the runaway growth of temperature. Thermal instability does not usually develop across the whole volume of the insulation but at local spots. The instability initiation is associated with the temperature rise of weak spots (spots with higher electrical conductivity, lower thermal conductivity or specific heat, electric field inhomogeneity due to electrodes configuration, and etc). Development of electrothermal instability can lead to elongation of the region with high temperature and conductivity in the direction of the field lines and propagation of the contracted conducting channel into the insulation [3]. After the bridging of the electrode gap by the highly conducting channel the current intensifies and temperature rises sharply that is insulation breakdown.

The phase transition of the dielectric material to highly conducting state occurs when the temperature of the dielectric exceeds a critical value. The discharge channel propagation is caused by the growth of the highly conducting state region into the insulator. The electric field, charge, and energy dynamics within the discharge channels and dielectric material governs the channel growth. The analytical investigation of thermal instability development presents considerable mathematical difficulties, resulting from interdependence and nonlinearity of the processes within the dielectric. A more adequate method of study of thermal instability is numerical modeling. For computer simulation the model has been created and realized as a 3D numerical algorithm within a cubic lattice on the base of finite-difference approximations of model equation.

The aim of the paper is to clear up the possibility of propagation of the highly conducting channel due to the development of the electrothermal instability under DC pulse voltage in solid dielectric material. The results of a numerical investigation of thermal instability development caused by a local high conducting inclusion are presented. Spatial-temporal characteristics of the discharge channel formations for BeO ceramics are obtained. The effects of conduction inhomogeneities on the channel propagation are discussed.

2. Model formulation

The model describes the dynamics of electric field potential φ, the free charge density ρ, temperature T and phase transition of the dielectric material from weakly to highly conducting phase. The phase transition occurs when the temperature of the dielectric exceeds the critical value T_c. The system of the model equations can be written as:

$$\nabla(-\varepsilon(\nabla^2\varphi) = \rho/\varepsilon_0 , \quad (1)$$

$$\partial\rho/\partial t = \nabla(\gamma\nabla\varphi), \quad (2)$$

$$C\partial T/\partial t + \beta\delta\ (T - T_c) = \nabla(\lambda\nabla T) + \gamma(\nabla\varphi)^2 \quad (3)$$

where ε is the relative dielectric permittivity, ε_0 that of free space, γ is the conductivity, C is the volumetric thermal capacity, λ is the thermal conductivity, β is the specific heat of the phase transition, T_c is the temperature of the phase transition, and δ is the Dirac function. Conductivity, thermal capacity and thermal conductivity of the material in both phases depend on the temperature.

The simulation region has rectangular shape: $0 \le x \le L_x$, $0 \le y \le L_y$, $0 \le z \le L_z$. The side z=0 corresponds to a grounded electrode $\varphi=0$, and the side $z=L_z$ to a potential electrode $\varphi=\varphi_0$. The cyclic boundary conditions for the potential and temperature are imposed on the lateral sides (x=0, L_x and y=0, L_y). The plane electrodes are assumed to be heat-insulated.

In the model the Arrhenius-type dependencies of the conductivity on the temperature are used both for weakly and highly conducting phases:

$$\gamma_i(T) = A_i \exp(-B_i/T), \; i=1,2, \qquad (4)$$

where A_i and B_i are parameters of the dielectric material, the indexes 1 and 2 correspond to the weakly and highly conducting phases, respectively. Dependency of the conductivity on the electric field is left out of account.

3. Electrothermal instability

For dielectric material BeO ceramics parameters were assumed. The following dependencies and parameters were used for the simulation: $C_1=4.79\cdot10^6+$ $+1058.2\cdot T$ J/K·m^3, $C_2=8.46\cdot10^6$ J/K·m^3, $\beta=9.1\cdot10^9$ J/m^3, $\lambda_1=55.65-0.033\cdot T+6.25\cdot10^6\cdot T^2$ W/K·m, $\lambda_2=12.4$ W/K·m, $T_c=2843$ K [4, 5]. Measured dependence of specific resistivity on temperature is given in Fig. 1. Conductivity parameters of equation (4) are approximated as $A_1=1242.7$ Om^{-1}·m^{-1}, $A_2=365.1$ Om^{-1}·m^{-1}, $B_1=30000$ K, $B_2=9900$ K. The simulation region size was 1 mm^3. Features of the electrothermal instability development are determined mainly by the conductivity dependence on temperature $\gamma(T)$ and phase transition. Therefore, to investigate the basic characteristics of the thermal instability development the permittivity of the material in both phases are assumed to be constant.

The electrothermal instability development is considered for plane-plane geometry of electrodes. The high conductivity inclusion was placed in the center of simulation region. Conductivity of the inclusion is five times greater than conductivity of dielectric bulk. The local increase of temperature and conductivity results in formation of the electric dipole about thermal perturbation and oriented along the applied field (Fig. 2). So the growth of electrothermal structure in direction of the applied field occurs – simultaneously with the increase of the amplitude the half-width of the perturbation grows along the applied field (axis z) and decreases across (axis x), see Fig. 3, 4.

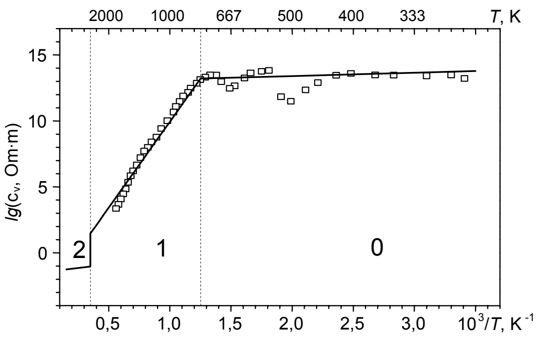

Fig. 1. Specific resistivity vs. temperature for BeO ceramics

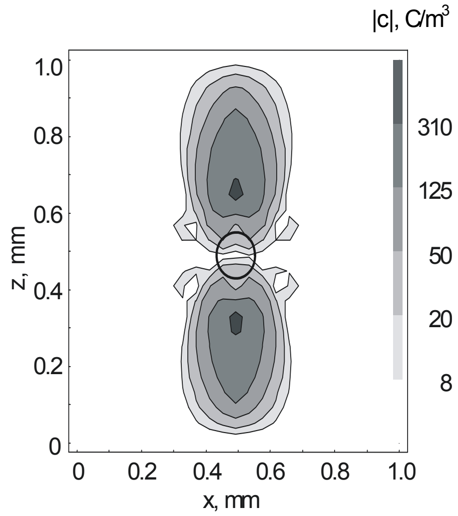

Fig. 2. Charge density modulus distribution. Position of high conductivity inclusion is marked as circle

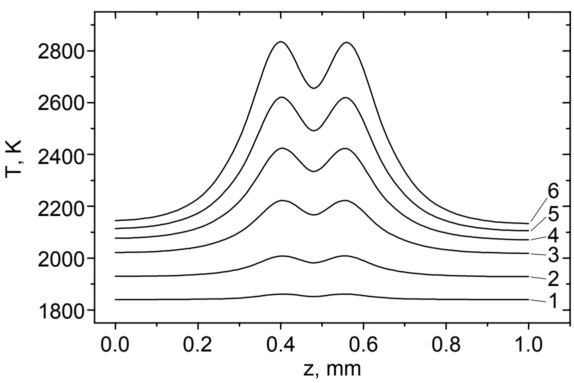

Fig. 3. Temperature profiles along field. Moments of time: 1–0.3 ms, 2–0.7 ms, 3–0.9 ms, 4–0.96 ms, 5–0.99 ms, 6–1.0 ms

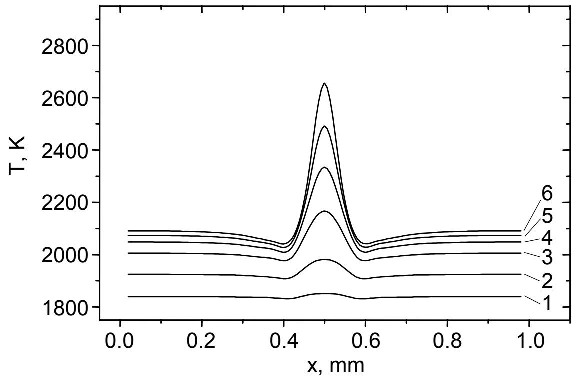

Fig. 4. Temperature profiles across field. Moments of time: 1 – 0.3 ms, 2 – 0.7 ms, 3 – 0.9 ms, 4 – 0.96 ms, 5 – 0.99 ms, 6 – 1.0 ms

4. Discharge channel formation

The discharge channel development is considered for needle-plane geometry of electrodes. The bottom side corresponds to the grounded electrode $\varphi=0$ and the upper side with the needle at centre have the potential $\varphi=\varphi_0$.

Application of the rectangular voltage impulse results in the heating of the dielectric. The power of Joule heating is the most intensive in the local region near the needle tip. At low temperature dispersion of the thermal energy is dominated and nearly uniform heating with maximum near needle tip is observed. At some moment γ time became less than the characteristic time of temperature perturbation dissipation. So heating near needle tip starts to prevail. Thus in this place temperature reaches the critical temperature T_c and the phase transition occurs while temperature in bulk dielectric remains far from critical value. The time from voltage application till starting of phase transition is time of initialization. This time depends on initial temperature of dielectric and amplitude of applied voltage (Fig. 5).

The region of the highly conducting phase grows from the needle tip in direction of the plane electrode and becomes similar to a channel. Thus contraction of the current and formation of the narrow highly conducting channel in the dielectric occurs (Fig. 6 here and further applied voltage – 100 KV, initial temperature of dielectric – 1500 K, the times corresponding to the frames are the following: 1 – 15.7 ms, 2 – 16.0 ms, 3 – 16.4 ms, 4 – 16.8 ms after the voltage application).The propagation of the channel associated with formation of the charged region at the channel tip (Fig. 7) and consistent redistribution of the electric potential in the dielectric. Thus in front of the channel tip the region of the strong electric strength arises (Fig. 8). Just in this place the Joule heating is most intensive and the phase transition takes place resulting to the further growth of the channel. After the highly conducting channel bridges the gap the conductivity, current, and temperature rise sharply [6]. Time of channel growth is depend on applied voltage amplitude and almost initial temperature independent (Fig. 9) [7].

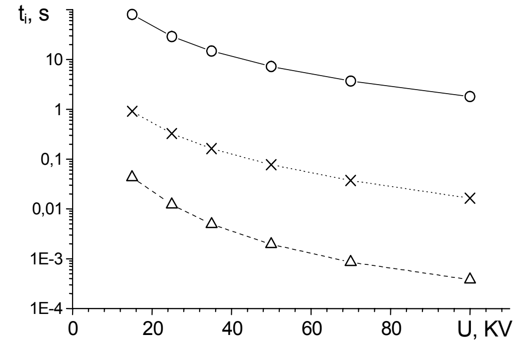

Fig. 5. Time of initialization, initial temperature of dielectric: o – 1200 K, x – 1500 K, ∆ – 1800 K.

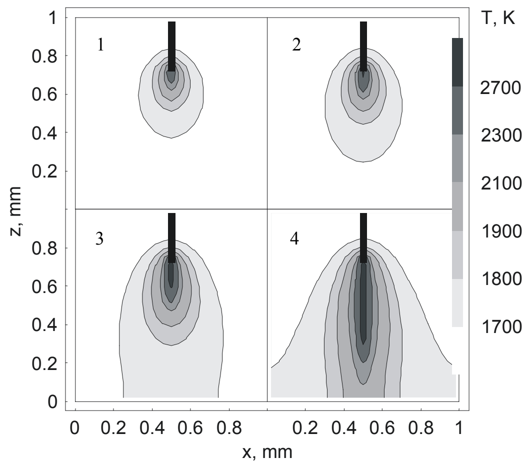

Fig. 6. Temperature distribution.

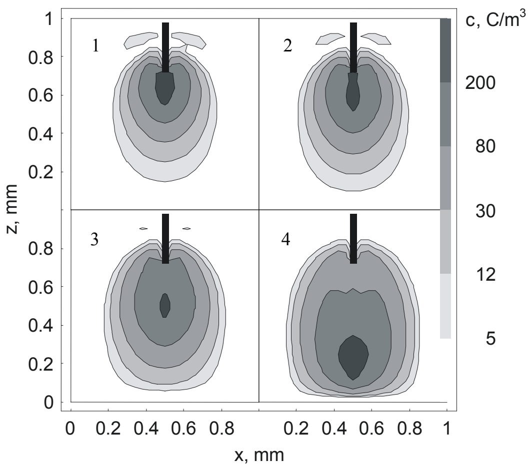

Fig. 7. Charge density distribution

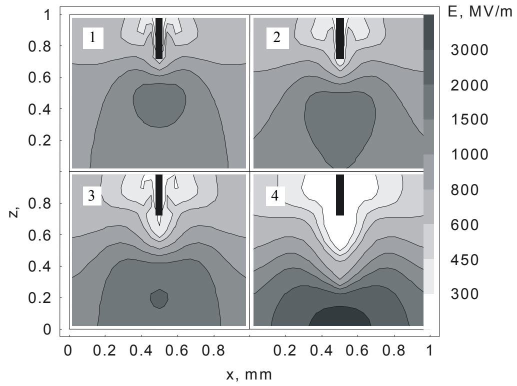

Fig. 8. Distribution of electric field

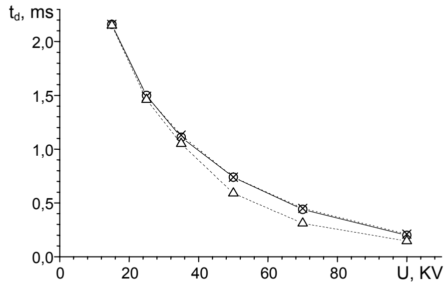

Fig. 9. Time of channel growth, initial temperature of dielectric: o – 1200 K, x – 1500 K, д – 1800 K.

4. Effects of conduction inhomogeneities

Conductivity inhomogeneities of the dielectric materials can result in formation of space charges in the regions with non-zero gradient of conductivity. The space charges cause the electric field redistribution within dielectric materials. The discharge channel growth is governed by electric field. Therefore the conductivity and permittivity inhomogeneities can affect the discharge channel trajectory even they are wide apart. Effect of the inhomogeneity depends on its shape, because the shape determines the location of space charges within the insulation bulk. We illustrate these effects of the elliptical inclusion with conductivity, which is different from the conductivity of the basic dielectric.

The simulation shows that the discharge channel trajectory passes through the highly conducting inclusion. This effec t is explained by the electric field distortion. The electric field intensification near the inclusion results to attraction of the discharge channel (Fig. 10, frame 2). When the channel gets in touch with the inclusion the maximum of the field occurs at the opposite side of the inclusion. If the inclusion conductivity is very high the channel stops and a new channel can start from this place. In a case of not very high conductivity of the inclusion the Joule heating is most intensive within the inclusion and the channel propagates through it and comes out the opposite side of the inclusion (Fig. 10, frame 3). Under certain condition a bifurcation of the channel can take place. One channel propagates towards the highly conducting inclusion but other channel grows in the direction of the opposite electrode.

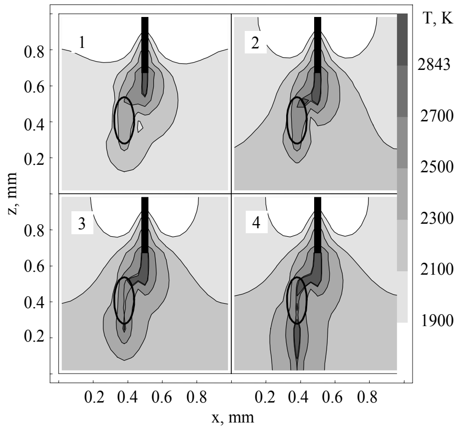

Fig. 10. Channel trajectory alteration caused by of high conducting inclusion

6. Conclusion

Development of the electrothermal instability in the dielectric results in elongation of the phase transition region and formation of the narrow highly conducting channel between the electrodes. The time of channel growth is weakly dependent on the initial temperature and much shorter than the time of breakdown initialization. Thermal breakdown is improbable in case of uniform fields and homogeneous dielectric properties. Nonlinear interaction between the electric field, the temperature, the charge density results in discharge channel trajectory passes through the highly conducting inclusion.

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