Fluctuation model of the breakdown of liquid dielectrics

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Extensive experimental data indicate the importance of stochastic processes in the breakdown of liquid dielectrics: the statistical lag time between application of the voltage over the gap and the start of breakdown, the asymmetric structure of the system of streamers, and the lack of reproducibility of the form of the discharge and the place where it originates. It is interesting to note that because the system is far from equilibrium, the branching structure of the conducting zone can have a fractal (nonintegral) dimension.

One of the first attempts to simulate the form of these structures was the work of Sawada and his colleagues,[1] which was based on the model of the development of cell colonies, (Iden, 1961). Niemer, Pietronero, and Wiesmann[2] took the next step and related the probability of growth to the potential difference at neighboring lattice points of the computational grid (i.e., with an electric field). The potential distribution is found from the solution of Laplace's equation outside growing structure, which corresponds to the limit of an equipotential conducting phase. This model has been used in numerous papers for different geometries of the gap between the electrodes for two and three-dimensional breakdown.[3-6] However, in this approach there are a number of fundamental drawbacks: the dependence of the discharge on the electric field does not have a threshold and there is no statistical lag time before the start of breakdown. In addition, for fast nanosecond discharges in condensed dielectrics the basic assumption of this model that the conducting phase is an equipotential can be incorrect. The absence of complete charge relaxation along the conducting branches is indicated, for example, by experimental data showing that for fast discharges the propagation velocity from anode to cathode does not increase sharply as one approaches the discharge, as it would if charge relaxation and therefore extrusion of the electric field were able to occur.

In the limit where complete charge relaxation cannot occur for small build-up times of the breakdown structure, the field will not differ strongly from the pre-breakdown field E_0. This is obviously the case for nanosecond breakdown ($\tau \sim 1$ ns) during the formation of primary streamer channels, whose electrical conductivity is below $\sigma \sim 1$ S/m (Refs. 7, 8).

In Refs. 8 and 9 the dynamics of a streamer discharge in solid and liquid semiconductors was studied and the numerical solution for breakdown took into account the finite mobility of the charge carriers generated by thermal dissociation and ionization. The calculations show that for $E_0 \sim 10^9$ V/m breakdown proceeds from the anode with the characteristic time $t \sim 10$ ns and $\sigma \sim 0.1$ S/m. The maximum field strength in the conductivity wave propagating from the anode to the cathode at each instant of time cannot increase and does not exceed $E \sim 5E_0$ (complete charge relaxation does not occur). This mechanism dominates for nanosecond breakdown from an anode at high pressure, where the bubble mechanism is suppressed.[10]

This mechanism is considered in the present paper. It is assumed that the growth process is described approximately by a threshold-type criterion: if the local field is $E > E_* + \delta$ then a new section of conducting phase is produced in the region.[11] Here E_* is a characteristic of the material; physically it is the average (ideal) threshold field for breakdown, and δ are the random fluctuations of the critical field. There are many causes of the random component, the most important of which is the statistical nature of the excited states of the vibrational degrees of freedom of the molecules and the electronic configurations. Another important factor is the spatial inhomogeneity of the dielectric. Obviously, negative fluctuations δ are the most important. Large fluctuations are statistically rare and occur in the far wings of the distribution.

The condition for breakdown is determined by the local electric field E, which depends on the voltage applied to the gap and its geometry, and also on the local configuration of

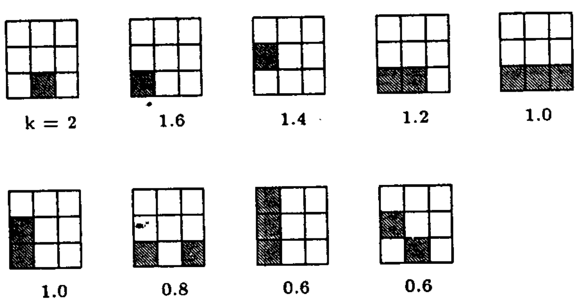

FIG. 1. Anisotropic cellular automaton: the central cell becomes conducting if $E > E_* + \delta$, where $E = kE_0$.

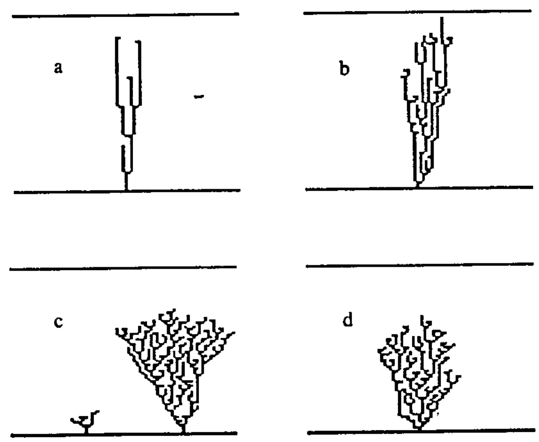

FIG. 2. Breakdown structures for a) $E_0 = 1.0$, b) 1.1, c) and d) 1.15 ($E_* = 2$, arbitrary units). 80 × 80 grid.

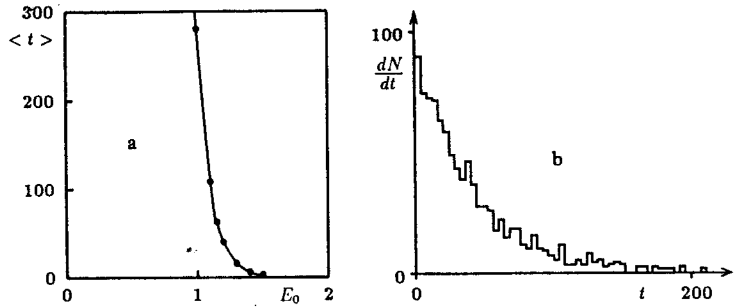

FIG. 3. a) Dependence on E_0 of the average lag time $\langle t \rangle$ of the start of breakdown; b) distribution function of the lag time of the start of the breakdown for $E_0 = 1.2$ (number of events = 1000).

the conducting structure in the neighborhood of the point in question. In particular, the field is weaker near the thicker ends of the gap. To take the structure factor into account the model of so-called cellular automata, was used.

In contrast to ordinary difference methods, in the models of cellular automata first proposed in 1948 by Von Neuman and Ulam, not only space and time are discrete, but all of the other physical quantities can take on only a finite set of discrete values. In addition, the rule for the determination of the new state of each cell depends on the local values of the functions only in the neighboring cells. In the case of two-dimensional breakdown between parallel electrodes an anisotropic cell, automaton is constructed where the local field E is determined from a table of fundamental cell configurations of the states of neighboring points of the grid: $E = kE_0$ (Fig. 1). After the initial conditions are specified, the system evolves in time. Then the cellular automaton, taking into account the fluctuations of the critical field at the point in question by the Monte Carlo method, produces one or another configuration of electrical breakdown.

This approach is similar in concept to the lattice gas models[12] widely used in computer simulations, where a deliberate reduction in quantitative information about the process makes it possible to describe the growth of instabilities and even to obtain the qualitative features of the fundamentally nonlinear later stages of the process.

By the implementation of this model in the present paper it was possible to obtain all of the basic qualitative effects observed experimentally.[7,10,13-15]

Figure 2 shows the simulation results for several values of the initial applied electric field. As the initial field strength increases the growing structure, which is quite asymmetric, increasingly resembles a brush discharge, and secondary and higher-order growing structures may also be generated. For constant initial parameters of the process the place of origin and the detailed form of the discharges are stochastic in nature.

To construct the dependence of the average lag time $\langle t \rangle$ of the start of breakdown on the applied electric field E_0 a large number of numerical experiments were performed (400 for each point). The decreasing dependence observed experimentally[15] is clearly reproduced (Fig. 3a), as well as the threshold nature of the breakdown: $E_{cr} \approx 1$ for $E_* = 2$ (arbitrary units). For lower fields the lag time increases sharply and in this case breakdown can actually occur earlier by means of the bubble mechanism.[15]

For a fixed E_0 information of importance is the average time $\langle t \rangle$ as well as the form of the distribution function dN/dt. The histogram obtained for $E_0 = 1.2$ is shown in Fig. 3b and explains the experimental results.[10] Its form is qualitatively the same for different distribution functions of the fluctuation δ, since it should resemble the Poisson distribution when the probability of breakdown is small at each time step.

It is straightforward to use this method to simulate the birth and growth of breakdown structures in three dimensions.

In the framework of the approach discussed here it was possible to take into account the basic stochastic aspects of breakdown without analyzing the physical mechanism on a microscopic level. This shows the importance of probabilistic processes, which are taken into account in the model in the form of fluctuations in the local threshold condition for breakdown. In deterministic physical models the propagation of the conducting phase in the breakdown of a condensed dielectric[8] can model only symmetric growth of a unit initial perturbation on the electrode. A complete description of the breakdown mechanism could be obtained by a judicious combination of the fluctuation model with the model of Ref. 8.

The condition for the critical field strength has a quite general meaning. In particular, it does not contradict the hypothesis that streamer channels propagate by means of brittle fracture of the continuous medium caused by the local electric field near sharp points of a streamer.[16,17]

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