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Dielectric Surface Effects on Transient Arcs in Lightning Arrester Devices

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A calculation focused on the avalanche growth of electrical current in a composite insulator consisting of an air gap and a solid dielectic. The results show that trapped charge can quench the electrical breakdown. The results are compared with phenomena found in dielectric barrier discharge (DBD) devices.

I. INTRODUCTION

One of the earliest and most simple electrical breakdown problems involves two electrodes separated by air as the electrically insulating material [1, 2]. A more complicated structure that retains this simple geometry involves a second insulating material, a solid dielectric. This basic structure consists of an electrode, air gap, solid dielectric and another electrode. A form of this basic structure has practical applications as a device to create ozone through chemical reactions stimulated by the electrical discharge [3]. The particular breakdown phenomena in these structures is called dielectric barrier discharge (DBD) [3]. In this case, the dielectric barrier helps to limit the electrical breakdown [4, 5]. The electrical discharge deposits charge into the solid dielectric; the resultant electric field quenches the discharge. Solid insulating dielectrics were developed for use in lightning arresters composed of spark gaps. [6, 7]. For this purpose, the dielectric reduces the time for the discharge growth. This time duration, called the formative-time, must be short to make the device effective as a protective device. A related structure, called a lightning arrestor connector (LAC), has a similar function but it is more complicated because it is in the form of a coaxial cable connector.[6–9]. Finally, extensive work on the formative-time of breakdown has revealed that is is reduced and controlled by the presence of dielectric particles on the surface of a cathode electrodes [10]. In this case, the solid dielectric serves as sources of electrical discharge [10].

The calculations to be discussed are focused on the effect of the solid dielectric on the initial transient currents in these dielectric barrier structures. One concern is the initial growth of the transient current. Another is the quenching of this current caused by electrons trapped in the solid dielectric. This latter matter is the focus of this paper.

The starting point for reasoning about transient discharge is the classic Townsend avalanche breakdown [1, 2]. The basic idea is that an electric field accelerates electrons in the gas to high enough energies that they release additional electrons from the gas molecules. The first released electron releases another electron and then these two electrons release more electrons. This effect is called an avalanche. The initiating electron is often regarded as provided by background ionizing radiation. However, it may originate from the solid dielectric. For the calculations to be discussed, the primary mechanism is not known. Thus, in order to make progress, two different mechanisms are used. One calculation focuses on the growth of an avalanche and another calculation focuses on the quenching of an avalanche by electrons trapped in the solid dielectric.

II. THEORY

The calculations to be described focus on avalanche breakdown in a simple structure. The continuum reactive transport equations include the species in the gas, solid dielectric and the electrodes. The calculations involve continuity equation for the mobile species such as electrons, holes and atoms. The interactions are governed by electrochemical potentials and chemical reactions. One noteworthy consideration is the inclusion of breakdown and chemical reactions in all the materials, the gas, the solid dielectric and the electrode. In previous work, the effects of electrodes and solid dielectrics are usually included in the form of boundary conditions [11–15].

For this paper, the calculations are made very simple but the materials and their interfaces are included. The only species included are electrons and holes. The ions in the gas are assumed to exchange charge at the interfaces to release holes. In future work, the gas interactions at interfaces will be included. The kinetic equations for the electron n and ion (hole) p densities are:

$$\frac{dn}{dt} = \frac{1}{q}\nabla\mathbf{J}_n + \frac{\alpha}{q}\left|\mathbf{J}_n\right| + S_n \quad (1)$$
$$\frac{dp}{dt} = -\frac{1}{q}\nabla\mathbf{J}_p + \frac{\alpha}{q}\left|\mathbf{J}_n\right| + S_p. \quad (2)$$

In these continuity equations, the second terms represents Townsend avalanching and the last term represents sources and sinks of electrons and holes. The currents are

$$\mathbf{J}_n = qn\mu_n E + qD_n\nabla n$$
$$\mathbf{J}_p = qp\mu_p E - qD_p\nabla p$$

In this expression, the Townsend avalanching term is

$$\alpha = AP\exp(-BP/E) \quad \text{(alpha)}$$

in which P is the pressure [11–15]. The Poisson equation

$$\nabla^2\phi = \frac{\rho}{\varepsilon\varepsilon_0}$$

is solved to obtain the electric field $E = -\nabla\phi$ in terms of the charge density:

$$\rho = p - n.$$

In this paper, the Townsend equation parameters are obtained from previous work on electrical breakdown of air [16]. The values are

$$A = 14.6 \text{ Torr}^{-1}\text{-cm}^{-1}$$
$$B = 365 \text{ V-Torr}^{-1}\text{-cm}^{-1}$$

III. CALCULATIONS

These initial calculations focus on a simple one-dimensional structure whose insulating region is composed of an air gap and the solid dielectric. This composite insulator is between two electrodes. The air gap has a thickness of 10 μm, and the solid dielectric has a thickness of 1 μm. The two electrodes are taken to be heavily doped Si regions. In these calculations, only the air gap is allowed to undergo electrical electrical breakdown.

The calculations shown in Fig. 1 show the growth of a Gaussion distribution of electrons placed near the cathode on the left hand side. These electrons are the "seed" electrons that drift to the anode because a positive electrical potential has been applied to the anode. Diffusion causes this Gaussian pulse to become wider as it propagates. In addition, the avalanche term causes growth of both the electron and hole densities during this process. Finally, the electrons enter the solid dielectric region where the avalanching ceases. The electron density drops in this region because it flows rapidly out through the electrode. The hole density is larger than the electron density in this region because the electrodes are assumed to not inject charge. Thus the holes are not able to flow to the cathode.

Similar calculations show the effect of the electrons being trapped in the solid dielectric by a uniform distribution of defects. Figure 2 shows the growth in charge density for this case, and figure 3 shows evolution in the electrical potential as the trapped charge grows. For these calculations, a thermal pulse applied to the cathode causes thermionic emission of electrons. Similar to the case of the ionizing wave, the electron and ion densities both grow. Figure 2 shows that the trapped charge density becomes comparable with the charge induced on the anode electrode. As a consequence, the electric field becomes smaller until the avalanche ceases. In effect, the trapped electrons and the opposite charge in the right hand side electrode form a dipole that opposes the applied electrical bias.

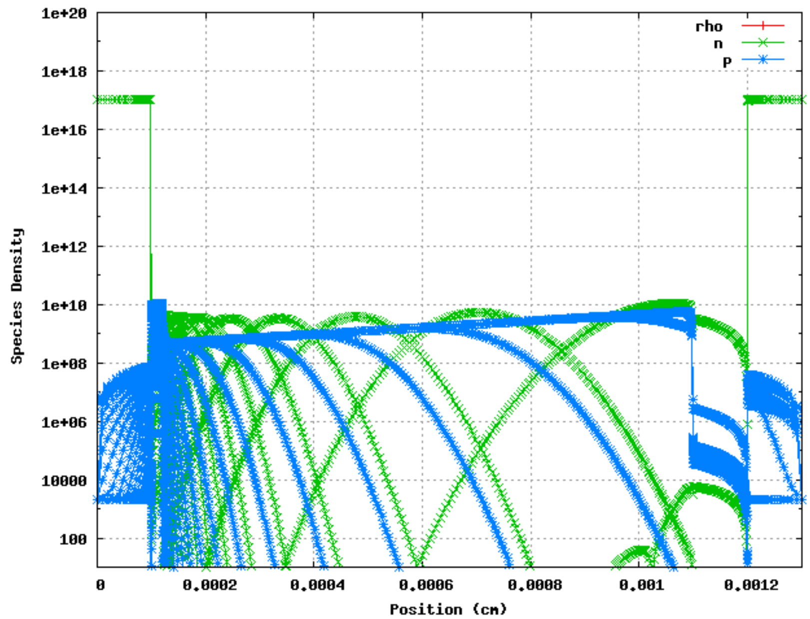

FIG. 1: Shows an ionization wave propagating from the cathode to the anode.

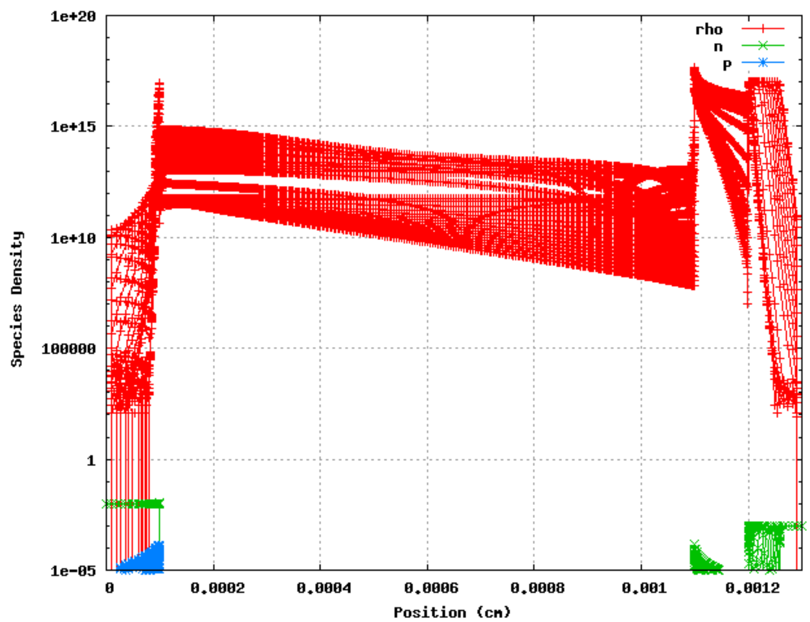

FIG. 2: The electrons are trapped in the solid dielectric on the right hand side.

IV. DISCUSSION

The qualitative effects are similar to those observed in calculations focused on DBD structures [13–15]. In agreement with these calculations, the charge in the solid dielectric causes an electric field that quenches the discharge. These results suggest that trapped charge should also quench electrical breakdown in lightning arrester and lightning arrester connector (LAC) devices.

In future work more details involving the solid dieletric will be incorporated. For example, the process by which charge from ions is transferred to the electrodes will be included.

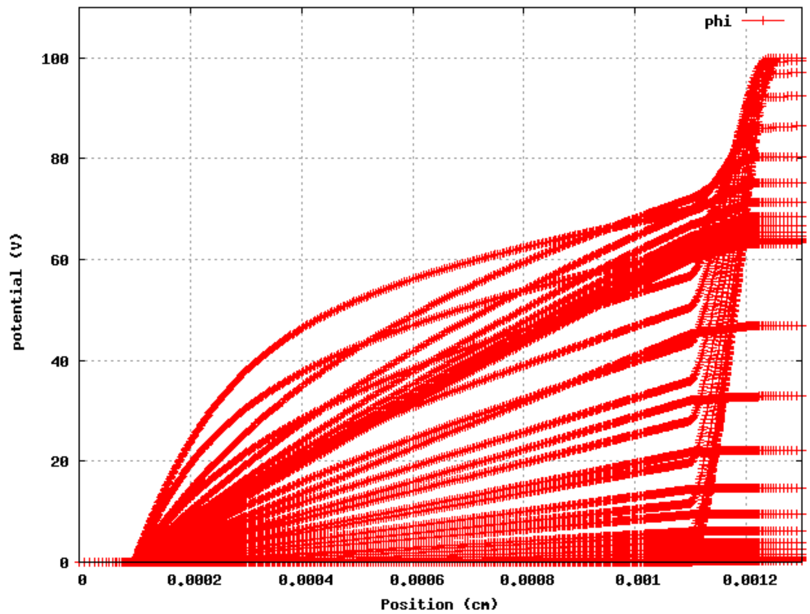

FIG. 3: The electrical potential in the air gap is reduced by the trapped charge. This causes the electrical breakdown to be quenched.

V. SUMMARY

These calculations illustrate the effects of defects in a solid dielectric. Such defects trap electrons, the resultanct electric field quenches the avalanche.

VI. ACKNOWLEDGMENT

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