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Electric Field Dependence of the Time to Electrostatic Breakdown in Insulating Polymers

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Abstract

Electrostatic breakdown can be thought of as the point at which a buildup of local defects in insulators leads to a catastrophic change in electric-conductivity. Defects can be produced by temperature, radiation, or a prolonged exposure to constant electric fields. The endurance time is the time it takes to generate enough defects to create a conduction path for electric current to flow more readily. The literature for electrostatic breakdown in polymeric highly disordered insulating materials discusses two competing theories for electrostatic breakdown, based on generation of either recoverable defects or irrecoverable defects. Such defects in the polymer chains can be produced by the electric field and result in localized trapped states for the conduction electrons. Both mechanisms are characterized by the density of electron traps and the corresponding energy to create such defects. We propose a hybrid thermodynamic model for the electric field aging process that predicts the mean time to failure (the endurance time) as a function of applied electric field and temperature. The hybrid model incorporates both types of defects, and proposes an interdependence of the two production mechanisms. Measurements of the dependence of endurance time on electric field in the insulating polymer Low Density Polyethylene (LDPE) were fit against this hybrid model. Lower electric fields produced breakdown times of 4 to 1 hr and were associated with creation of irrecoverable defects. Lower electric fields resulted in breakdown times on the order of 2 hours to several months; these were associated with recoverable defect generation. Intermediate range electric fields produced interesting results that illustrate the interdependence of the two types of defects. We end with consideration of an important application of the research. Charge buildup on insulating materials in the space environment can produce long exposure to electric fields, which can lead to breakdown at lower fields. This charge buildup is the leading cause of spacecraft failure due to space environment interactions [1]. Understanding the electric field dependence of the time to electrostatic breakdown can assist designers in selecting appropriate materials for spacecraft construction and in mitigating these destructive processes.

Electric Breakdown Theory

Electric aging occurs when the molecular bonds in a material are disrupted. In polymeric insulators, this electric aging causes a breakdown described as electrostatic breakdown or discharge (ESD). The literature has shown that electric aging can be characterized by the barrier energy between bond sites, bond destruction energy or cohesion energy, trap creation within the material, and stress upon the bonds due to local and applied electric fields [2, 3, and 4]. The barrier energy between bond sites is given by an energy of activation which has been directly measured by experiments [5]. The barrier energy decreases by the applied stress electric field, temperature, and time.

The literature describes two competing processes that explain the endurance and breakdown dependence of the applied stress for insulating polymers [2, 3, and 4]. The first process is the creation of new traps (broken bonds) resulting from charge injection on molecular scale (Fig. 1). This process can cause breakdown events that begin by a local stress event. The second process describes the breakdown being caused by the direct stress applied to the segments leading to permanent damage (Fig. 2). The stress of this set of events is lower than the critical stress for breakdown. These two processes can be described as a rate process of the reconfiguration and de-cohesion of the bonds. These recoverable events are evidenced by spikes in the measured current prior to breakdown and are observed at the electric field F_{break} (Fig. 3 and 4). The first process described here is the breakdown caused by the direct stress applied to the segments leading to permanent damage (Fig. 2). The second process described here is the breakdown caused by the direct stress applied to the segments leading to permanent damage (Fig. 2). The stress of these events is lower than the critical stress for breakdown. These two processes can be described as a rate process of the reconfiguration and de-cohesion of the bonds. The process is described in higher details.

The United States University Materials Physics Group (USU MPG) has developed a model that bridges the two processes and provides a way to calculate an increase in trap concentration (rate of bond breaking) as a function of time and applied stress [5]. This model is the USU MPG dual mechanism multiphase trapping model given by:

\[ F_{break}(t) = F_{break}(0) \left( 1 + \frac{t}{\tau_{break}} \right) \]

The model captures the activation energy, the number of density defects, the rate of defect formation, and the probability function, \( F_{break} \) being the time to breakdown. The activation energy, \( Q \), the number of density defects, \( n_{def} \), and the probability function, \( F_{break} \), are the fitting parameters of the model. Planck's constant, \( h \), Boltzmann distribution constant, \( k \), and the permittivity constant \( \epsilon \), are fundamental physical constants. The value of \( Q \) is the material's dielectric constant and a property of the material. The applied field \( F_{break} \) and temperature \( T \) are variables that can be changed with each test.

Results

In the pre-breakdown region, the material being tested acts as an infinite resistor and negligible (<1 µA) current is passed. At breakdown, the current increases significantly (>200 µA) and maintains a constant value until breakdown is achieved, as indicated by the limited resistance in the circuit (Fig. 6). Tests conducted on the insulating polymer Low Density Polyethylene (LDPE) indicate the mean time to breakdown of LDPE occurs at (277 ± 8) MΩ and is the upper bound before which endurance time is achieved.

The measured values for the Gibbs activation energy and activation volume are \( Q = 3.00 \text{ eV} \) and \( \Delta V = 3.50 \text{ eV} \), \( \Delta T = 10^{-3} \text{ cm} \), and \( \Delta V \), \( 10^{-3} \text{ cm} \). Several spikes in the current (highlighted regions of Figs. 8 and 9) can be seen before breakdown. These are the recoverable breakdown events that occur only after the critical field value has been reached twice, which eventual breakdown is only a matter of time.

Figure 8 shows the measured breakdown current density for different applied fields, and the correlation with the theoretical model. Figure 9 shows a comparison between the experimental and theoretical models, and confirms the theoretical model is accurate.

Future Work

Preliminary data on the electric field dependence of the temperature at electrostatic breakdown has been taken for LDPE. Future studies will expand this data to better understand the how the electric field at breakdown is affecting the aging process of the material in the range of 30 to 300 K. Furthermore other useful insulating materials will be studied; e.g. Kapton, Teflon, and silicone, which materials exhibit differing density of defect states and will provide additional reliability to the USU MPG model and the theories for the creation of defect states by an applied electric field.

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References