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

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Abstract

Understanding the breakdown of insulators under prolonged high voltage stress is enhanced by application of the USU MPU atomic scale model. Model predictions of the lifetime of the polymeric insulator under these conditions have important applications on a small scale in electrostatic components and on a large scale on electrical circuits, high voltage insulators, high voltage tower transmission lines (Fig. 11), insulator standards and ESD LDPE Data and USU MPG Group, USA.

A common recurring problem in the space environment is the accumulation of electrostatic charge on the surface of spacecraft and its internal components [1]. Such charging can result from a variety of mechanisms, including direct charge injection (electric field on the craft), is prevalent on the insulating materials used, and can lead to electrostatic breakdown. Our model can even lead to eventual failure of multi-million dollar satellites.

Identifying how the electrostatic breakdown (ESD) of polymeric insulators depends on temperature and the time they are exposed to such charge accumulation (or electric field) is key to predicting, and extending, the lifetime of the spacecraft. Extreme environmental conditions [2, 6] and far distances away from Earth in which spacecraft such as the James Webb Space Telescope (Fig. 13) operate require that the engineers and scientists designing them must be able to account for such effects in order to prolong the operational lifetime of the spacecraft.

Electrostatic 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 is increased (or decreased) by the applied stress (electric field, temperature, etc.).

The literature describes two competing processes that explain the enhancement 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 molecules (Fig. 10.1). This process is called a recoverable breakdown event and may lead to a significant increase in the lifetime of the material (Fig. 2a) and 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 not present at the electric field Fbreakdown (Fig. 1, 8, and 11). The second process describes the breakdown caused by the direct stress applied to the segments leading to permanent damage (Fig. 10b); this is known as the irreversible breakdown. This process is dominated at higher fields (Fig. 2b).

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

\[ \frac{d\text{defr}}{dt} = \text{defr}_0 \left( \text{exp}\left(-\frac{E_b}{kT}\right) - \frac{\text{defr}}{\text{defr}_0} \right) \]

with \( \text{defr}_0 \) being the time to breakdown. The activation energy, \( E_b \); the number density of defects, \( n_0 \); and probability function, \( \text{defr}_0 \), are the fitting parameters of the model. Planck’s constant \( h \), the Boltzmann distribution constant \( k_B \), and the permittivity constant \( \varepsilon_0 \) are fundamental physical constants. The value of \( n_0 \) is the molecular dielectric constant and a property of the material. The applied field \( F \) and temperature \( T \) are variables that can be changed with each test.

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 irreversible 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. Upper electric fields produced breakdown times of 4s to 1hr and were investigated with creation of irreversible 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.