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

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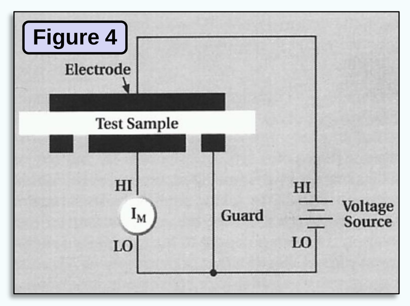
Experimental Chamber



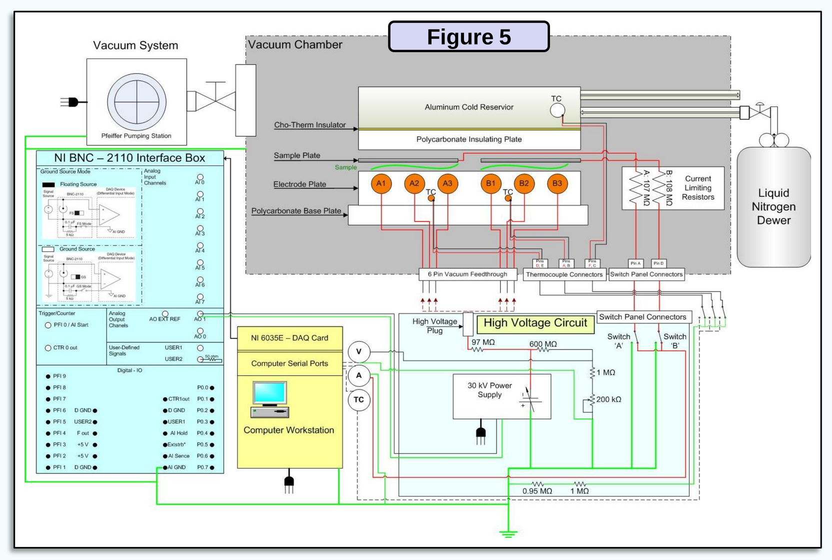


Figure 4. A simple parallel plate capacitor assembly for the ESD test circuit.
Figure 5. Electrostatic Discharge Chamber test circuit detailed schematic and diagram. Created June 29th, 2011 by Charles Sim and Matthew Stormo.

Tests were conducted in a custom, high vacuum chamber in a simple parallel plate capacitor assembly designed by the Utah State University Materials Physics Group. The concept behind the parallel plate capacitor ESD assembly can been seen in Fig. 4. However this diagram lacks the detailed setup that is required to carry out these experiments. A more detailed schematic is necessary to provide a clear analysis of any problems with the system (Fig. 5).

Samples were clamped between a metal sample mounting plate and six Cu high voltage electrodes (Figs. 6 and 7). Voltage is applied to a copper electrode using a variable high voltage power. The voltage is incremented at a rate of 20 V every 4 s until the target voltage has been reached or breakdown has occurred. Current and voltage are monitored using two interfaced multimeters under LabVIEW control. Two 100 MΩ resistors are used to the limit the current in the circuit after complete breakdown occurs.

Measurements for the time endurance of electrostatic breakdown (see Fig. 2) were conducted by ramping the applied voltage to a target plateau voltage and maintaining a static electric field over the sample until breakdown occurred. Endurance time to breakdown, t_{en}, was measured from the moment an electric field was applied.

Target voltages for the endurance time experiments were in the range of 4000 V to 9000 V. These values yield endurance times from a few seconds to a few days.

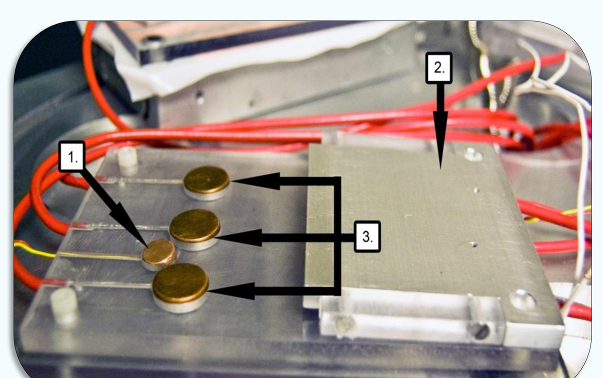


Figure 6. Exposed view of ESD sample assembly. (1) Cu thermocouple mount, (2) Sample and mounting plate, (3) Cu high voltage electrodes.

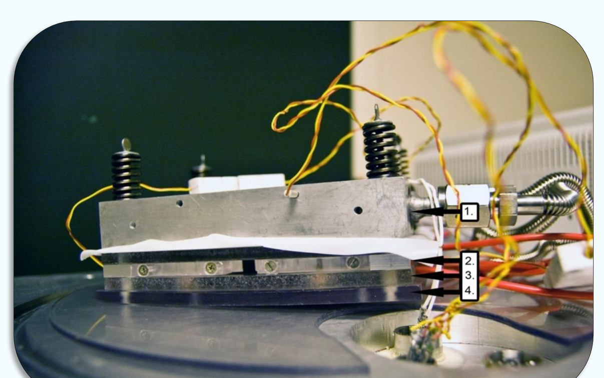


Figure 7. Interior view of ESD sample assembly. (1) Cryogen reservoir, (2) Sample mounting plate, (3) Electrode plate with 2 sets of 3 high voltage copper electrodes and a Cu thermocouple mount, (4) Polycarbonate insulating base.

Results

In the pre-breakdown region, the material being tested acts as an infinite resistor and negligible (<10 μA) current flows. At breakdown, the current increases significantly (≥10 μA) and maintains a constant slope set by the current limiting resistance in the circuit (Fig. 8). Tests conducted on the insulating polymer Low Density Polyethylene (LDPE) indicate the mean room temperature breakdown field occurs at (277 ± 8) MV/m and is the upper bound below which endurance time tests were conducted.

The measured values for the Gibbs activation energy and activation volume are ΔG_A = 0.90 eV and ΔG_B = 3.50 eV; $\Delta V_A \sim 10^{-20}$ cm³ and $\Delta V_B \sim 10^{-19}$ cm³ [6].

Several spikes in the current (highlighted regions of Figs. 8 and 9) can be seen before breakdown. These are the recoverable breakdown events that only occur after the critical field value has been reached beyond which eventual breakdown is only a matter of time.

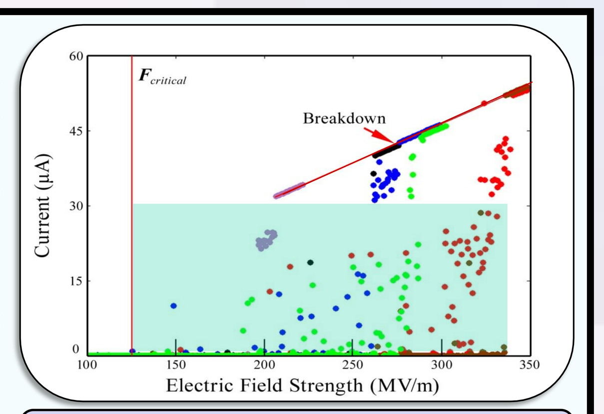


Figure 8. Six I-V curves of current as a function of applied voltage, where voltage is ramped at 20 V increments at 4 sec intervals until breakdown.

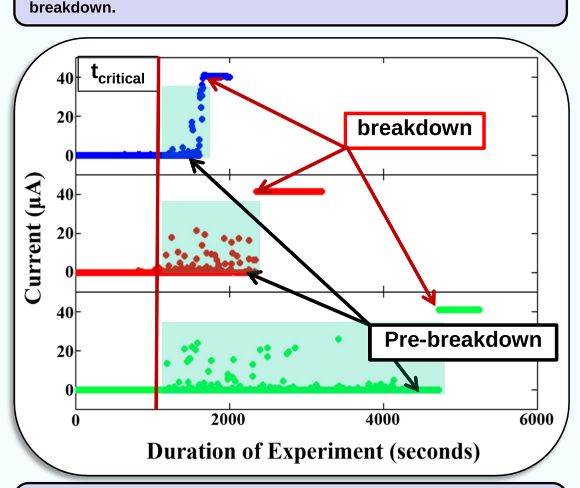


Figure 9. Three endurance curves of current as a function of time, where the applied voltage is ramped up to a set value and then allowed to sit until complete breakdown occurs. This method isolates constant applied voltage behavior from that of the ramping rate.

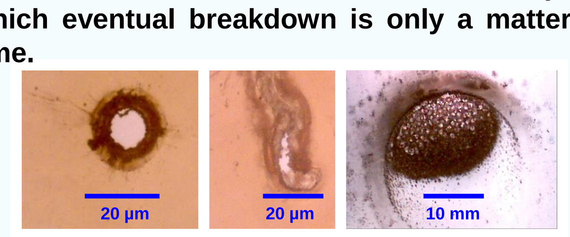


Fig. 10. Images of breakdowns. Kapton E usually breaks down with circular holes (left), while LDPE is more irregular (center). ePTFE can breakdown rather spectacularly (right).

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 electrical 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. Higher electric fields produced breakdown times of 4 s 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.

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 can be modified (increased or decreased) by the applied stress (electric field, temperature).

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 due to the creation of new traps (broken bonds) resulting from charge injection on molecular segments (Fig 1a). This process (called a recoverable breakdown event) requires less energy to begin, is dominant at low electric fields (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 onset at the electric field $F_{critical}$ (Fig. 3, 8, and 9). The second process describes the breakdown being caused by the direct stress applied to the segments leading to permanent damage (Fig. 1b); this is known as the irrecoverable breakdown. This process is dominant at higher fields (Fig. 2b).

The Utah State University Materials Physics Group (USU MPG) has developed a model that bridges the two processes and provides a way to calculate the 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 multiple trapping model given by:

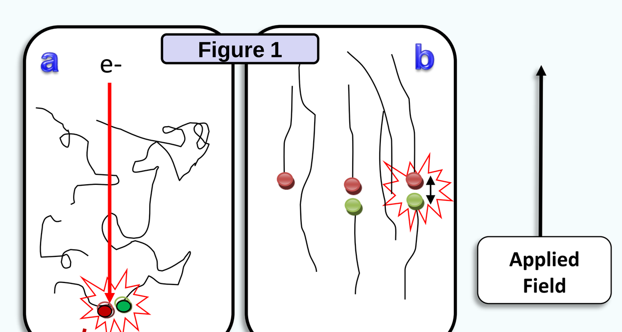
$$t_{breakdown}(F,T)=\left(\frac{h\Delta\nu_0(F,T)}{2k_bT}\right)\exp\left[\frac{\Delta G(F,T)}{k_bT}\right]\mathrm{csch}\left[\frac{F^2\varepsilon_0\varepsilon_r\Delta V_{def}(F,T)}{2k_bT}\right]$$

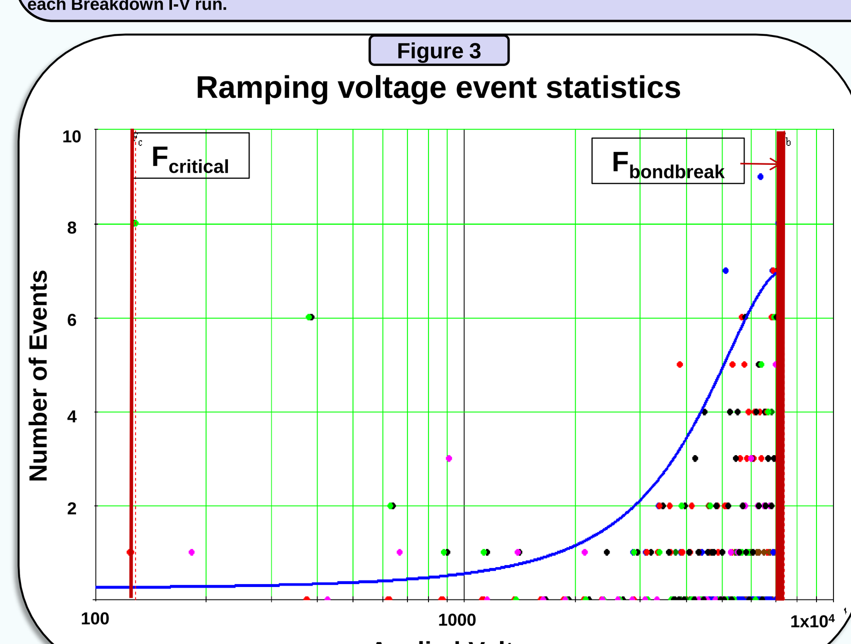
with $t_{breakdown}$ being the time to breakdown. The activation energy, ΔG; the number density of defects, n_{def} (); and probability function, Δv_0, are the fitting parameters of the model. Planck's constant h, the Boltzmann distribution constant k_b, and the permittivity constant ε_0 are fundamental physical constants. The value of ε_r is the relative dielectric constant and a property of the material. The applied field F and temperature T are variables that can be changed with each test.

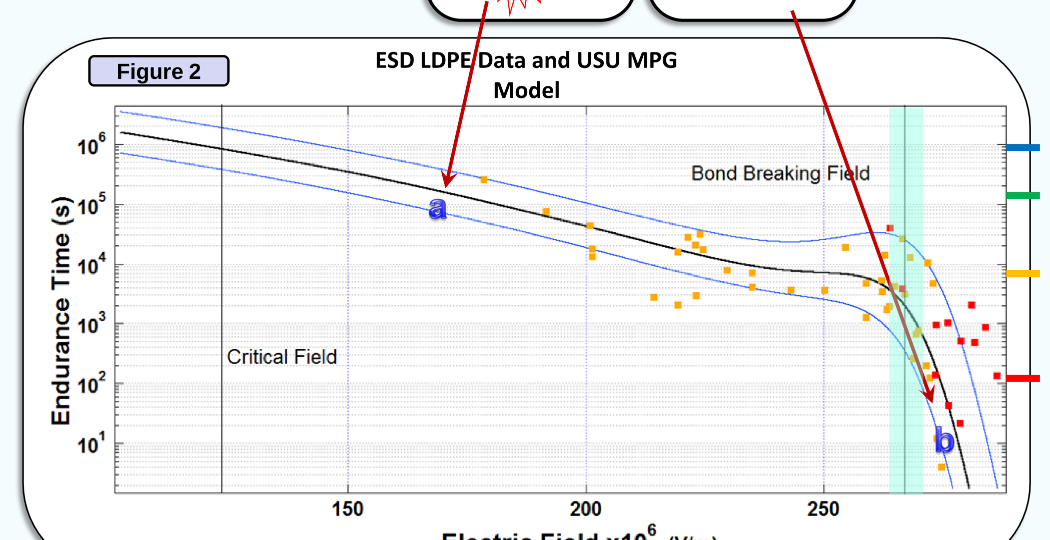
Figure 1. Breakdown processes a and b. Process a, recoverable breakdowns: Breakdown of the material is due to creation of new traps resulting from charge injection and impact ionization of molecular or crystalline segments. Process b, irrecoverable breakdowns (F > $F_{bondbbreak}$): Breakdown of the material is due to direct stress on molecular segments causing irreparable damage with no bond repair possible.

Figure 2. USU MPG dual mechanism multiple trapping model fit against endurance time data for the polymer LDPE. (a) Breakdown process dominated by the reconfiguration and de-cohesion of molecular bonds acted upon by charge injection. (b) Breakdown process dominated by direct stress of the electric field acting on the molecular bonds causing permanent damage. The colored lines to the right indicate the following time scales on the graph: 1 minute, 1 hour, 1 day, 1 week.

Figure 3. A statistical analysis conducted of the many observed short duration, recoverable breakdown events or "current spikes" observed during each Breakdown I-V run.







Applications

Understanding the breakdown of insulators under prolonged high voltage stress is enhanced by application of the USU MPG atomic scale model. Model predictions of the lifetime of the polymeric insulator under these conditions have important applications on a small scale in electronics components and on a large scale on electrical circuits, high voltage insulators, high voltage power transmission lines (Fig. 11), insulator standoffs [7], and spacecraft.

Figure 11. High voltage power transmission lines. Photo by Dennis Richardson

A common recurring problem in the space environment is the accumulation of electric charge on the surface of spacecraft and its internal components [1]. Such charging creates a voltage potential (electric field) on the craft, is prevalent on the insulating materials used, and can lead to electrostatic breakdown. (Fig. 12) It can even lead to eventual failure of multi-million dollar satellites.

Figure 12. ESD event lead to severe damage of this solar array.

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 [8] 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 take in to account charging issues in order to prolong the operational lifetime of the spacecraft.

Figure 13. Scale model of the JWST.

Future Work

Preliminary data on the electric field dependence of the temperature at electrostatic breakdown have been taken for LDPE. Future studies will seek to expand this data to better understand the how the electric field at breakdown is affected by a change of temperature in the range of 75 K to 300 K.
Furthermore other useful insulating materials will be studied; e.g. Kapton, Teflon, SiO_2. These 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.

Acknowledgements

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