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Defect-Driven Dynamic Model of Electrostatic Discharge and Endurance Time Measurements of Polymeric Spacecraft Materials

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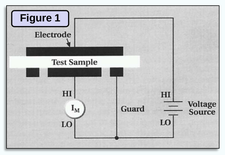
Experimental Chamber



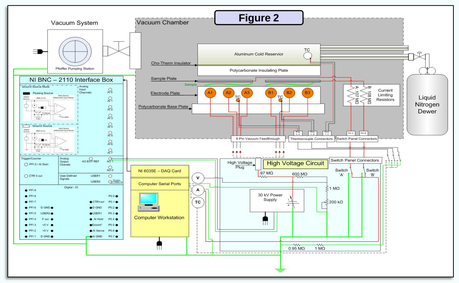


Fig. 1. Simple parallel plate capacitor assembly for the ESD test circuit.

Fig. 2. Electrostatic Discharge Chamber test circuit detailed schematic.

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, shown in Fig. 1. A more detailed schematic of the system is shown in Fig. 2.

Samples were clamped between a metal sample mounting plate and six Cu or graphite foam covered high voltage electrodes (Figs. 3 and 4). Voltage was applied to the electrode using a variable high voltage power. The voltage was incremented at a rate of 21 V every 4 s, until the target voltage was reached or breakdown had 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. 10) were conducted by ramping the applied voltage to a target plateau voltage and maintaining this static electric field 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.

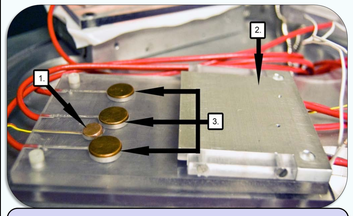


Fig. 6. Exposed view of ESD sample assembly. (1) Cu thermocouple mount, (2) Sample and mounting plate, (3) Cu high voltage electrodes.

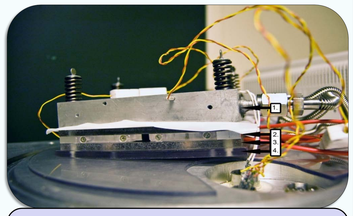


Fig. 7. Interior view of ESD sample assembly. (1) Cryogen reservoir, (2) Sample mounting plate, (3) Electrode plate with 2 sets of 3 high voltage copper electrodes and a Cu thermocouple mount, (4) Polycarbonate insulating base.

Acknowledgements

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Abstract

Charge buildup on insulating materials in the space environment can produce long exposure to electric fields, which can lead to Electrostatic Discharge (ESD). Charge buildup is the leading cause of spacecraft failure due to space environment interactions. ESD can be thought of as the point at which the buildup of charge in localized defects, found in polymeric insulating materials, leads to a catastrophic change in electrical conductivity, which can cause the materials to structurally breakdown. Defects produced by radiation, or prolonged exposure to electric fields, significantly alter the endurance time, the time it takes to produce enough defects to generate a current path to flow more readily. The literature discusses two competing theories for ESD in insulators, based on generation of either recoverable or irrecoverable defects. Such defects in the polymer chains can be produced by the electric field and result in localized trapped states for conduction electrons. Both mechanisms are characterized by the density of electron traps and the corresponding energy to create such defects. We propose a hybrid model for the aging process that predicts the endurance time as a function of electric field and temperature. The model incorporates both types of defects with an interdependence of the two mechanisms. Measurements of the endurance time dependence on electric fields in the insulating polymer Low Density Polyethylene (LDPE) are fit against this hybrid model. Understanding the electric field dependence of the time to ESD can assist designers in selecting appropriate materials for spacecraft construction and in mitigating destructive processes.

Electrostatic Breakdown Theory

Electrical aging causes breakdown in insulating materials. Aging in the spacecraft environment is induced by high energy particle flux into or though the material, medium to high applied fields, and contact carrier injection. It has been shown by many authors that electrical aging can be characterized by the Gibbs free energy for bond destruction, trap creation within the material, and bond stress due to local and applied fields.

Assuming that an applied field produces a pressure on a defect, we find that the pressure is related to the permittivity times the square of the field (1). The defect energy is simply the pressure times the effective volume over which the field acts. In most cases, the effective volume is proportional to the inverse of the density of states (10^{18}-10^{20}) cm^{-3}. The average cohesive bond energy associated with (weak Van der Waals bonds and main chain reconfiguration energies such as chain kinks) can be estimated as (2-10 meV) and using (1) one can estimate the minimum field at which recoverable defects might begin to occur, called the critical field F_{onset} ~ 4 MeV/m. Such energies are low enough that thermal fluctuations can lead to defect annihilation. Further, we can estimate complete bond breaking energy as (0.6 eV - 0.9 eV) giving F_{bb}~270 MeV/m.

$$1 \quad E_{defect} = \frac{1}{2}(F_c)^2(\epsilon_0\epsilon_r\Delta V)$$

And this yields the critical onset and bond breaking fields

$$F_{onset} = \sqrt{\frac{E_{recoverable}}{(\epsilon_0\epsilon_r\Delta V)}} \quad F_{bb} = \sqrt{\frac{E_{irrecoverable}}{(\epsilon_0\epsilon_r\Delta V)}}$$

This model, based on rate theory and the idea that the bond breaking kinetics should be similar to kinetic rate reactions in chemical systems, provides a way to calculate the increase in trap concentration, (broken bonds) as a function of time and temperature (3). Stress acts on the bond energies (Gibbs energy of activation ΔG) to reduce the energy necessary to start the degradation process (Fig 12). For simple average molecular interactions, a process can be envisioned where the field increases or decreases the Gibbs energy. On average it is expected that the forward and backward movements of on-chain carriers, chain reconfiguration and free chain elements can be thought of as a rate process (2). The rate of bond breaking due to the field, Gibbs activation energy ΔG, activation volume ΔV, temperature T, and applied field F are the physical parameters of the system. Using (2-3) one can obtain (4).

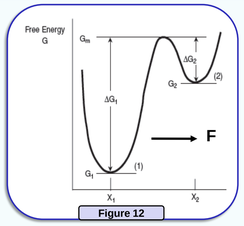

Figure 12

The measured endurance time data in Figure 11 shows that there is a definite transition between two separate regimes, suggesting that a new composite model incorporating at least two mechanisms is required. Consider two breakdown processes a and b in Fig. 10. In process a, the breakdown of the material is due to creation of new traps resulting from charge injection and impact ionization of molecular or crystalline segments. This process requires less energy to initiate (activation energy), allows for spontaneous repair of broken bonds, and is dominant at fields below the bond breaking field, where the ends of broken bonds with unpaired sites will act as electron traps. As the injected charge becomes trapped in the ionized molecular segments and on chain segments, a high localized field develops leading to breakdown. In process b, the breakdown of the material is due to direct stress on molecular segments causing irreparable damage with no bond repair possible. In this process there, is little ionization or segmental motion.

$$2 \quad K^{\pm}_{bb} = \frac{kT}{h} exp\left[-\frac{\Delta G_{bb} \pm \epsilon\Delta V_{bb}F^2}{2kT}\right]$$

$$3 \quad \frac{dn_{bb}(t)}{dt} = K_{bb}[F,T,n_{bb}(t)](N_t - n_{bb}(t)) + K_{br}[F,T,n_{bb}(t)]n_{bb}(t)$$

$$t_{end}(F,T) = \left(\frac{h\,P(F,T)}{2k_bT}\right)\exp\left[\frac{\Delta G(F,T)}{k_bT}\right]\mathrm{csch}\left[\frac{F^2\varepsilon_0\varepsilon\Delta V_{def}(F,T)}{2k_bT}\right] \quad 4$$

t_{end} is the time to breakdown. The activation energy, ΔG; the number density of defects, n_{def} ; and probability function, P 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. A dual mechanism model has been developed that provides a way to calculate the increase in trap concentration (rate of bond breaking) as a function of time and applied stress [5]. The probability of breakdown during a time Δt while the sample is held at field F is the sum of breakdown for each of the mechanisms: (5).

$$P(F,T) = \sum_{\substack{i=dual\\ mechanisms}} \left(\frac{2k_bT}{h/\Delta t}\right)\exp\left[\frac{-\Delta G_i(F,T)}{k_bT}\right]\sinh\left[\frac{F^2\varepsilon_0\varepsilon\Delta V_i(F,T)}{2k_bT}\right] \quad 5$$

Analysis of Breakdown Results

Pre-Breakdown Analysis

In the pre-breakdown region, the material being tested has very high resistance and negligible (<10 μA) current flows. Several spikes in the current (green highlighted regions of Figs. 5, 6 and 11) can be seen before breakdown. These are the short duration, recoverable breakdown events that occur only after the critical field value, F_{onset}, has been reached, beyond which eventual breakdown is only a matter of time.

A statistical analysis has been conducted on the many "current spikes" observed for 65 breakdown I-V runs. This analysis yields critical information about the nature of ESD, arcing, and the distinction between recoverable and irrecoverable breakdown.

The frequency of pre-breakdown arcs is shown in Fig. 8. The estimated amplitude of a single arc is 0.2±0.1 μA. At higher electric fields, measured arc currents are larger, suggesting that multiple arcs-typically of ~1 μs duration—have occurred during the ~0.5 s data acquisition times of the multimeters. The frequency of arcs is fit with an exponentially increasing function (see Fig. 9) with amplitude N_0=3.1 Hz and onset energy F_{onset}=53 MV/m.

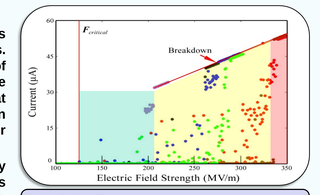

Figure 5. Six I-V curves of current as a function of applied voltage, where voltage is ramped at 21 V increments at 4 sec intervals until breakdown.

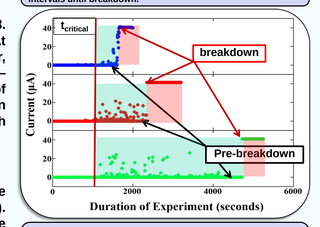

Figure 6. Three endurance curves of current as a function of time, where the applied voltage is ramped up to a set value and then maintained until complete breakdown occurs.

Breakdown Analysis

At breakdown (red regions), low resistance paths are formed and the current increases significantly (≥10 μA). After breakdown, a constant slope is maintained set by the current limiting resistance in the circuit (Fig. 5).

For insulating polymer Low Density Polyethylene (LDPE) 27 μm thick samples, the mean room temperature breakdown field occurs at (277 ± 8) MV/m and is the upper bound below which endurance time tests were conducted.

Figure 8

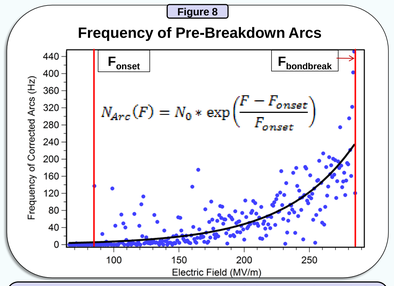

Figure 8. A statistical analysis conducted of the many observed short duration, recoverable breakdown events or "current spikes" observed during 65 breakdown I-V runs. The fitting parameters of the exponential function are N_0=3.1 Hz, F_{onset}=53 MV/m. $F_{bondbreak}$ is at 284 MV/m

Figure 9

$$N_{Arc}(F) = N_0 * \exp\left(\frac{F - F_{onset}}{F_{onset}}\right)$$

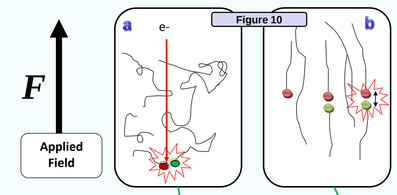

Figure 10

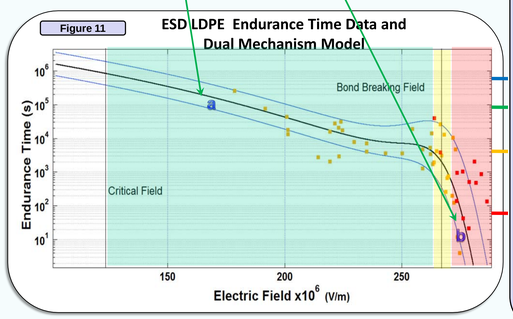

Figure 10. Breakdown processes a and b. Process a, recoverable breakdowns: Breakdown of the material is due to creation of new traps resulting from charge injection and impact ionization of molecular or crystalline segments. Process b, Irrecoverable breakdowns (F > $F_{bondbreak}$): Breakdown of the material is due to direct stress on molecular segments causing irreparable damage with no bond repair possible.

Figure 11. Dual mechanism multiple trapping model fit against endurance time data for the polymer LDPE. In addition, note the blue min and max lines. These are obtained by assuming a 2% deviation in ΔG and ΔV. This set of curves clearly gives an encompassing prediction of the possible spacecraft destruction times for applied fields. In fact, the most important line on this graph is the minimum blue line which gives the fastest possible time to breakdown. This is the important design curve.

(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.

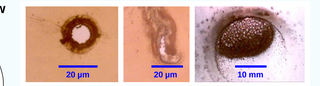

Fig. 7. Images of breakdowns. Kapton E usually breaks down with circular holes (left), while LDPE is more irregular (center). ePTFE can breakdown rather spectacularly (right).

Endurance Time Analysis

Tests on the endurance time to breakdown in the material LDPE were conducted at electric fields in the range of 172 to 280 MV/m.

Breakdown tests conducted in the range of 172 to 255 MV/m were dominated by the recoverable pre-breakdown process (Figs. 10a and 11a). Breakdown times observed in this range were on the order of a few hours to several days.

Tests conducted in the 265 to 284 MV/m range were dominated by the irrecoverable breakdown process. Breakdown times observed here were on the order of a few minutes to ~1 hr.

Tests conducted in the 260±5 MV/m range demonstrate a transition region, in which the irrecoverable breakdown process is beginning to dominate over the recoverable breakdown process as the electric field is increased. Breakdown times observed here are on the order of 1 to 10 hours.

Based on fits to the data using Eq. 5, the measured values for the Gibbs activation energy and activation volume are ΔG_{Pre} = 0.90 eV and ΔG_{BD} = 3.50 eV; ΔV_{Pre} ~ 10^{-20} cm^3 and ΔV_{BD} ~ 10^{-19} cm^3 [6].