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Measurements of Endurance Time for Electrostatic Discharge of Spacecraft Materials: A Defect-Driven Dynamic Model

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Abstract

Electrostatic discharge (ESD) is the primary cause of space environment induced failures and malfunctions. As mission lifetimes and the sensitivity and complexity of instrumentation increase, so does the need for describing the influence of the electrical aging processes on ESD. This research studies the electrostatic field strength (F_{ESD}) of polymeric insulators as a function of applied field and the time-to-breakdown for $F < F_{ESD}$. A dynamic physics-based model for time-to-breakdown is much more valuable than an empirical static model, since it provides the ability to predict the statistical lifetime of dielectric materials subjected to prolonged stress from sub-critical electric fields.

We present experimental results for two prototypical polymeric materials with different types of trap state densities, low density polyethylene (LDPE) and polyimide (PI or Kapton HN™). ESD tests were conducted by applying a high voltage across the material in parallel plate geometry, using a modified ASTM D149-99 method. F_{ESD} was determined as a sustained rise in I-V curves measured in a custom high vacuum chamber (<10^{-3}Pa). Ramp rates of ~20V steps at 4s intervals resulted in substantially lower F_{ESD} values than tests conducted with the maximum ramp rate of 500V/s recommended in ASTM D3755-97 standards. This suggests that values of F_{ESD} from standard handbooks or cursory measurements that have been historically used by the spacecraft charging community can substantially overestimate F_{ESD} in common spacecraft situations. In addition, for these polymers very short duration, unsustained arcing—termed pre-breakdown arcing—was observed at sub-critical fields well below F_{ESD} in these tests. Data were taken over temperatures from ~120K to ~300K. Time-dependent breakdown was studied with different tests, by applying a static field stress < F_{ESD} across the material and measuring the endurance time. Endurance times were measured from 10^0s to 10^5s, at voltages from near the nominal breakdown voltage down to < 50% of F_{ESD} at ~300K.

These experimental results are compared with thermodynamic mean field multiple trapping models of the electric field aging process and with limited available prior measurements. Numerous studies have shown that electrical aging can be characterized by defect creation within the material from bond stress due to local and applied electric fields and by the Gibbs free energy, bond destruction energy, or cohesion energy associated with creation of these defects. We introduce a first order approximation to develop an extended dynamic temperature-dependent electrostatic discharge model that both repairable and irreparable defect mechanisms. Repairable defect mechanisms such as bond bending have energies less than or comparable to thermal energies, so that they can be readily repaired through thermal annealing; irreparable defects such as bond breaking have higher energies. In the proposed mean field theory, each mechanism is characterized by a mean spatial separation of sites and a mean activation energy. The model predicts the observed measurements, which show a negative logarithmic decay of endurance time to electrostatic breakdown field. This is consistent with thermodynamic models, with F_{ESD} asymptotically approaching a constant value as the time-to-breakdown goes to infinity. Our studies of short unsustained arcs at sub-critical fields are also consistent with the repairable defect part of the theory. We also discuss these ESD results in terms of a more comprehensive unified theory for electron transport in highly disordered insulating materials, which allows a correlation between fitting parameters and more fundamental materials properties such as atomic scale structure and bonding, mobility, transition probabilities, and spatial and energetic distributions of trap states beyond the energy mean field approximation.

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