Dependence of Electrostatic Field Strength on Voltage Ramp Rate for Spacecraft Materials

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I. Introduction

The primary objective of this work investigated the dependence of electrostatic field strength for spacecraft materials on voltage ramp rate, by applying an increasing electrostatic field until electrostatic breakdown occurred. At high enough electrostatic fields or after long times, insulators can break down, causing large current flow through the material: this breakdown is called electrostatic discharge (ESD). Enhanced understanding of prolonged exposure to high static electric fields (DC aging) of insulating materials based on expanded experimental studies is critical to understand the physics of highly disordered insulating materials, as well as for applications in spacecraft charging. High voltage DC power transmission cables and switching, thin film dielectrics, and semiconductor devices and sensors [2].

II. Theory

A common mean field approximation for breakdown that considers only mean defect energy, $\Delta \varepsilon_{def}$, and mean defect density, $n_{def}$ is the Crone model [5,6].

$$P_{def} = \frac{2n_{def} \Delta \varepsilon_{def}}{k} \sinh \frac{2n_{def} \Delta \varepsilon_{def}^2}{2k}\left(1 + \sqrt{1 + \frac{2n_{def} \Delta \varepsilon_{def}}{k}}\right)$$

(1)

A first order approximation for how $F_{ESD}$ depends on the ramp rate $dv/dt$, comes by assuming that the ratio at two different ramp rates is the same for breakdown fields and the probability of breakdown. Setting the ratio of (1) evaluated at $\Delta t = \Delta t_{step}$ and $\Delta t = 1 \text{ s}$ equal to the ratio of the experimental ramp rate $t$ over $t_0 = 1$ and recalling that $\sinh^{-1} x = \ln(x + \sqrt{x^2 + 1})$ we find

$$F_{ESD}(x) = \frac{1}{\Delta t \Delta t_{step}} \left(1 + \alpha \Delta t \sinh \left(\frac{1}{2} \Delta t \alpha \Delta t_{step} \right)\right)$$

(2)

Note: (2) corrects a typographical error found in [4]. This approximation is quite simple but as it neglects much of the ramping process.

For incremental voltage step tests the breakdown probability, $P_{def}$, becomes

$$P_{def} = 1 - \prod_{i=1}^{n-1} \left(1 - \alpha \Delta t \sinh \left(\frac{1}{2} \Delta t \alpha \Delta t_{step} \right)\right)$$

(3)

Standard step-up voltage tests [8] were performed in a custom high vacuum chamber ($<10^{-5}$ Pa base pressure) at room temperature (see Fig. 1) [7]. Samples were placed between a metal sample mounting plate and six highly polished Cu high voltage electrodes, using the recommended 0.4 MPa uniform clamping pressure [8]. For ramp rate tests, voltage was incrementally increased at a constant time intervals until breakdown occurred, which was evident by an abrupt current increase followed by a ohmic linearly current above breakdown set by limiting resistors.

Figure 2 shows three step-up tests done at slow, medium, and fast ramp rates. Ramp rates shown in Fig. 2 vary from 20 V per 4 s to 2000 V per 4 s [4]; standard protocols suggest rates less than 500 V/s [7].

Between 3 and 6 tests were done at each ramp rate; each point in Fig. 3 shows the average and standard deviation of the tests at a given ramp rate. Figure 3 shows the breakdown field versus ramp rate for three polymeric materials, Kapton EPM (Pi), Kapton HNM (Pi), and bias-induced polypropylene (BDPP). Also shown are the average $F_{ESD}$ and a fit based on Eq. (2).

III. Methods and Results

Standard step-up voltage tests [8] were performed in a custom high vacuum chamber ($<10^{-5}$ Pa base pressure) at room temperature (see Fig. 1) [7]. Samples were placed between a metal sample mounting plate and six highly polished Cu high voltage electrodes, using the recommended 0.4 MPa uniform clamping pressure [8]. For ramp rate tests, voltage was incrementally increased at a constant time intervals until breakdown occurred, which was evident by an abrupt current increase followed by a ohmic linearly current above breakdown set by limiting resistors.

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Figure 2 clearly shows that faster ramp rates yield less information than the slow ramp rates.

- Faster ramp rates are limited by the resolution of the voltage step size, in which the case of fast ramp rates is quite large [see Fig. 2(a)].
- In contrast, the smaller step size in the slower ramp rate tests results in higher resolution and more continuous data [see Fig. 2(c)].
- The higher resolution data from lower ramp rates tests [Fig. 2(c)] exhibits more detailed physical information, including pre-arcing [7], field enhanced conductivity and possibly a threshold breakdown field strength, $F_{micro}$.
- Fig. 4 shows other information from slower ramp rate tests.

IV. Conclusions

- Initial Kapton ETPM ramp rate data showed strong dependence over a limited range of ramp rates, consistent with a proposed mean field theory, Eq. (2).
- Higher ramp rate data for Kapton HNM and BOPP showed little ramp rate dependence. Kapton HNM and BOPP data are consistent with a single average $F_{ESD}$.
- More data for additional ramp rates, lower uncertainties at a given ramp rate, and more diverse materials are required to test the applicability and accuracy of the mean value, mean field [Eq. (2)] and incremental voltage step [Eq. (3)] models.

- Slower ramp rates:
  - Better approximate spacecraft charging situations, where charging is most often very slow.
  - Allow higher precision and accuracy determination of $F_{ESD}$.
  - Produce data with more observable effects, such as pre-arcing and possibly field enhanced conductivity [7].

References