Measuring Charge Storage Decay Time and Resistivity of Spacecraft Insulators

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Abstract

An informal discussion of how accurate measurements of resistivity and increasing understanding of the behavior of insulating materials used on spacecraft is fundamental to advancing the design and utility of the spacecraft. Build up of charge can vary between different areas of the spacecraft, with excess charge accumulating and leading to functional anomalies or component failure. The most important parameter in determining how charge will decay through an insulator is the resistivity of the material. Current industry standards for measuring resistivity have been shown to be inconsistent with actual phenomena, and new methods of measuring resistivity must be developed and implemented. The charge storage method shows promise for both increasing the quality of measurement and gaining new insight into the interior behavior of insulators.

Introduction

The critical goal of all electronic equipment is to transfer to the correct location at the right time. Conductors are the vehicles of charge transport in a manner similar to the nervous system of the human body. Electrical impulses must travel and interact with a high degree of efficiency for the desired behavior to be achieved. Around the conducting element is an extensive support network of non-conducting, or insulating, material. The substrate of a circuit board protects the fragile wires within and prevents undesirable interference between them, much like the human backbone and skull serve to protect the spinal cord and brain. Beyond the protection of their conducting counterparts, these supporting materials have vital functions in their own right.

Aboard every piece of equipment that ventures out into the space environment, there are various insulating materials referred to as spacecraft insulators. They can be as basic as structural support and polymer coatings, the skin and bones of satellite anatomy. Or they can be complex, miniscule, and embedded into the circuits themselves. Their behavior can be strikingly different from that of conductors.

Understanding these insulating materials used to build that enable the spacecraft components to function correctly is the end goal of this research.

Problem Description

The space environment is hardly a sterile, friendly place where satellites can spend their lifetime gathering or transmitting data unaffected by what is around them. [1] Each of the Earth's orbits comes with conditions that must be taken into account when determining how the satellite's instruments will function.

As a first example, the spacecraft are bombarded with a spectrum of radiation during the part of their orbit that is exposed to the sun. Part of the satellite may be exposed to ions from the Earth's atmosphere, causing degradation of physical integrity. They travel through clouds and terrestrial weather-like storms of ions and plasmas. Each of these mechanisms bombards the materials of the satellite with charge, sometimes deeply embedding into the material.

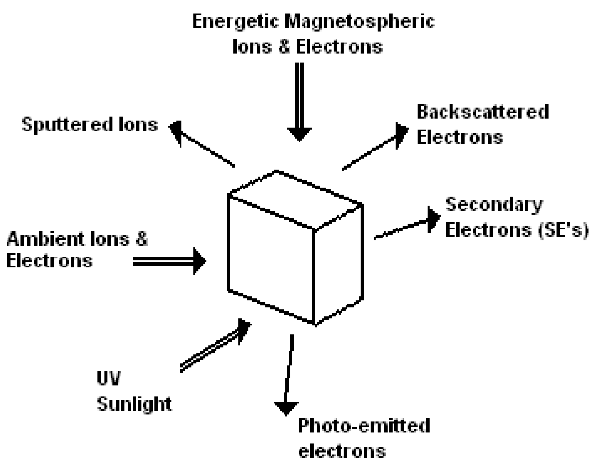

Fig. 1 – Various methods of charge transfer pertaining to spacecraft.

A perfect system would see the excess charge accumulated from the environment distributed equally over the body of the satellite or, even better, completely discharged away from the spacecraft. Since grounding the satellite to Earth isn't a viable option, it is hoped that the charge redistributes and decays during the period of the orbit that isn't exposed to significant charging effects.

Since insulators behave much differently from conductors, the charge does not redistribute evenly over the spacecraft. In fact, different insulating materials can collect and decay charge at different rates. If the excess charge gained by the material is not fully dissipated by the time it enters another charging period of the orbit, a net charge will begin to build within the insulator. Eventually all or portions this charge find a way out of the insulator to the conducting substrate or nearby conducting elements. In less some cases, the charge will discharge from the insulator surface in small, non-fatal pulses. This causes nearby conducting elements to pulse as well, sending small currents through surrounding wires. These small currents can result in a variety of effects, causing erroneous data to be recorded or increasing the noise of the electronic system. In severe cases, dielectric breakdown of the insulator occurs, compromising the insulator quality and possibly rendering components of the spacecraft unusable.

Tackling the problem of predicting if or when discharge events will occur is complex and tricky. A few of the questions that must be addressed are the method and magnitude of charge introduced to the satellite, how the charge is stored within the insulator, and the effects of the internal electric fields created by the accumulation of charge. Once charge is introduced into the insulator, how it accumulates and moves through the material is relevant to developing charging profiles that can be used to predict behavior.

These and other questions provide a rich variety of experiments that can be performed, hopefully with a return of information that will allow for the development of better experimental techniques. To illustrate the complexity of measurement, a few of the experiment types will be addressed.

Experimentation

Understanding the complex relationships between the spacecraft and its surroundings is fundamentally based on a detailed knowledge of how individual materials store and transport charge.

Instrumentation proves to be the first hurdle that must be overcome in the pursuit of quality data. While it is relatively well known what the spacecraft will encounter in the space environment, it is more difficult to accurately approximate that environment in a controlled laboratory setting. At the very least, the experiments must be performed in ultra high vacuum. Using the standard ASTM technique [2], Kapton^{TM} samples of varying thickness and initial voltages were tested in both atmospheric conditions, the current ASTM standard, and at a pressure of approximately 10^-4 torr. Table 1 lists resistivities and dielectric constants for the Kapton^{TM} with an aluminum coating.

The measured resistivity and dielectric constant diverge as the voltages increase, with the sample in vacuum showing little or no significant change in electrical properties while the sample in atmosphere changes substantially. This is not unexpected and provides a good check against other areas of research. There is a wealth of excellent work on the effects of high relative humidity and embedded water molecules on the behavior of conducting and insulating materials, believed to be the primary cause of this differing behavior.

Once a vacuum chamber has been constructed to operate at sufficiently low pressures, the battle is still far from won. Traditionally, under the guidance of the ASTM standards, the sample material is placed between two conducting surfaces in the configuration of a parallel plate capacitor.

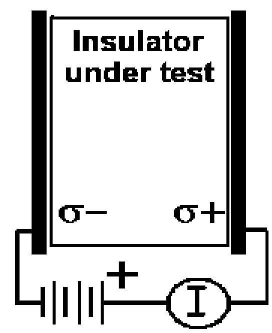

Fig.2 – ASTM method is a parallel plate capacitor configuration with the insulator sample acting as the dielectric inner material.

Applying a constant voltage across the plates for a set amount of time and then measuring the current through the insulator gives a value for the resistivity of the material. It is these resistivities, found via the classical ASTM method, which are recorded in handbooks and used to determine the

	Atmospheric Conditions			In Vacuum		
Initial Voltage	100 V	200 V	300 V	100 V	200 V	300 V
Dielectric Constant	19.1	20.6	22.1	19.2	19.2	19.4
Resistivity	6.3*10^11 Ohm-cm	6.7&10^11	7.2*10^11	6.2*10^11	6.3*10^11	6.3*10^11

Table 1 - Average dielectric constants and resistivities measured for Kapton^{TM} with one-side Aluminum coating in atmosphere and vacuum.

material's electrical properties. These are the same resistivities that have shown to be inconsistent with observed charging phenomena. [4,5,6] The question then becomes whether or not the right quantity is being measured and if it is being measured correctly. Modifying the ASTM method to include vacuum conditions reveals one type of discrepancy in the behavior of the insulator; another is discovered when current is measured over a longer time scale. A generic polyethylene film was kept at a constant voltage of 200 V for approximately one hour, with current measurements being made at varying rates. At one minute, the measured resistivity of the insulator was found to be 8.6 x 10^13 Ohm-cm. The final measurement, after one hour, was recorded as 2.0 x 10^14 Ohm-cm, a difference of nearly one full order of magnitude.

Manufacturer-given batch values for the resistivity of generic polyethylene range from approximately 10^11 to 10^13 Ohm-cm.

Plotting the current measurements over the course of the experiment provides an insight into the material's behavior.

The decay of current through the sample material follows the trend of an exponential decay, indicating that longer time scales provide better results. This provides another glimpse into what is happening inside the material under the presence of the applied voltage. Many polymers are complex chains of molecules that have the ability be strongly polarized. Accounting for the decay current in the material must then include more than counting the charge moving in and out of the material. How quickly the molecules within the insulator align with the electric field will

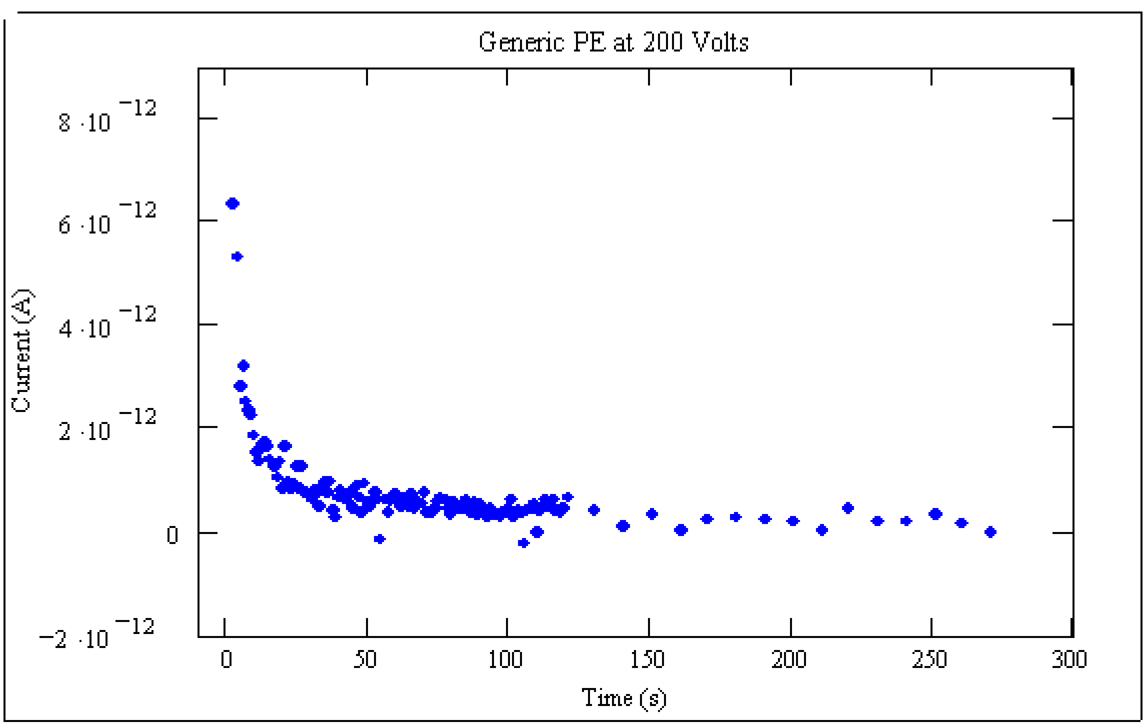

Fig. 3 – Current versus time for generic polyethylene film at 200 V for approximately one hour.

influence any charge transport through the material. The addition of polarization decay time then is necessary for any mathematical model attempting to approximate insulator behavior.

However, the problem changes shape again once a different type of material is tested. Whereas the generic polyethylene film had a relatively low resistivity, most spacecraft materials are highly insulating and have manufacturer given resistivities on the order of 10^17 Ohm-cm or more. Using a sample of Mylar™ with a thickness of 1 mil and one-sided coating of aluminum, the same experiment is repeated with the following results.

Although the magnitude of the current values are on the same order of those recorded for the generic polyethylene, the Mylar™ has a significantly larger standard resistivity of 10^16 Ohm-cm. If the same order of current is being read as before but this time resulting in what is obviously electrical noise, then there must be another aspect to consider.

Further testing reveals what appears to be an instrumental limit in the resistivities that can be measured. The results are subtle. Materials with resistivities up to the instrumental limit are clearly a variety of exponential decay while materials above the limit return mostly noise. The experimental uncertainty at those small values of current has not changed but no meaningful data is obtained.

General Conclusions

Only so much time and effort can be put into perfecting a method before alternatives must be sought. At this point, the classical ATSM method modified to perform in vacuum has reached the limit of its utility, and other avenues must be pursued.

One of the most promising new methods is the charge storage method. It has benefits both in the achieved quality of data and in a closer approximation of the space environment. Rather than

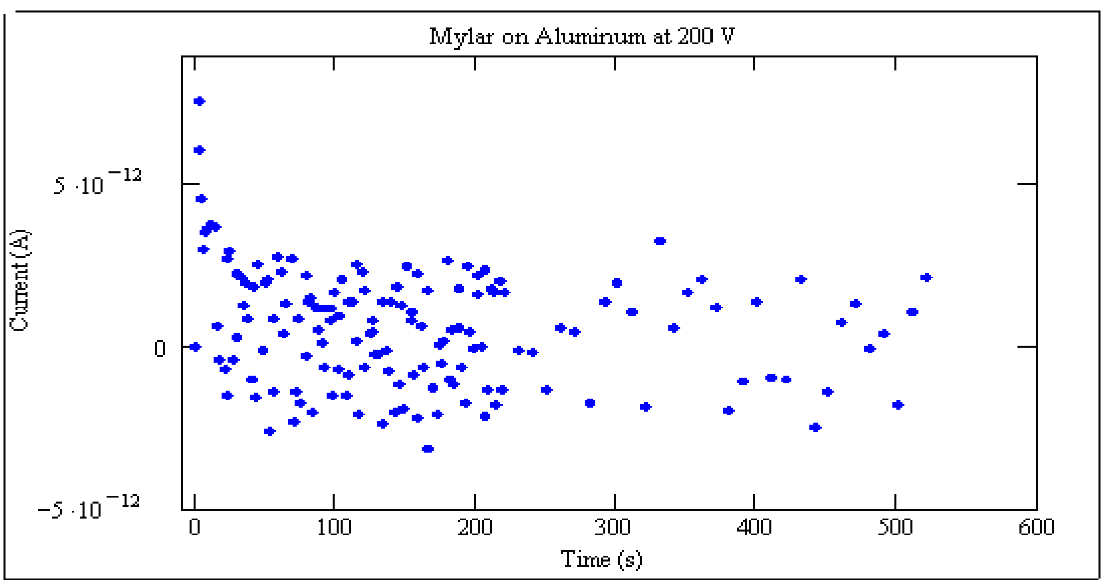

Fig. 4 - Current versus time for Mylar™ with one side aluminum coating at 200 V for approximately one hour.

placing the insulator between two plates and applying a voltage, the sample is attached to a conducting plate and left exposed in a vacuum chamber. The surface of the insulator can then be exposed to a variety of charging mechanisms, e.g. low energy electrons, ions, etc. In terms of decay times, those predicted by classical methods are usually less than a typical orbital period of the spacecraft, which range from a few hours to days. [3] This elapsed time allows the charge to dissipate before more charge is deposited. The results from the charge storage methods indicate that this decay time can be significantly longer than the lengths of standard orbital periods. Charge storage decay times on the order of weeks or even months prevent the spacecraft from effectively dissipating the charge deposited by the space environment and result in detrimental long-term charge accumulation.

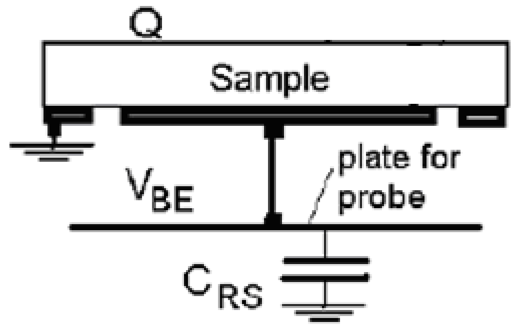

Fig. 5 – Simple diagram of charge storage sample mount and probe contact.

Preliminary tests have been performed for NASA at the Jet Propulsion Laboratory [4] while a next generation charge storage chamber is developed at Utah State University. An example of the obtained data is shown for a 40 mil sample of Alumina. The familiar exponential decay curve is seen. Data was taken over the course of a month, extending the time length even further to better ascertain the true decay time.

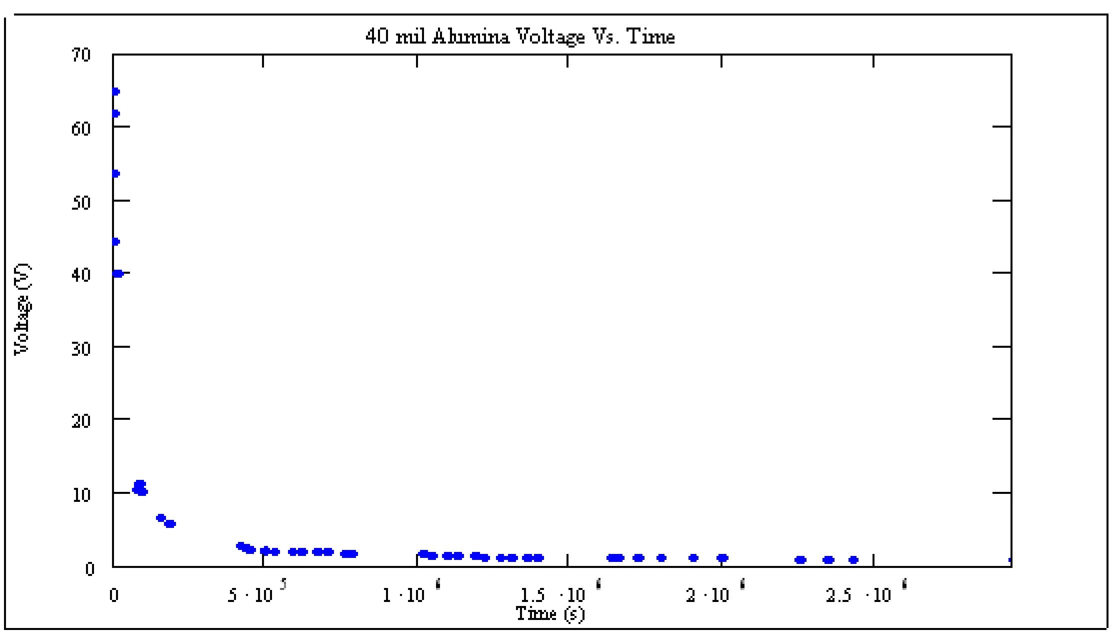

Fig. 6 – Voltage versus time data on 40 mil Alumina from Jet Propulsion laboratory using charge storage method.

The increased instrumental and methodological sensitivity of the charge storage method has allowed the development of a mathematical model for the charge decay in an insulator. Increased quality of data for highly resistive materials and use of longer experimental time lengths have uncovered a new batch of questions to be answered. The polarization of the material appears to play a more dominant role than first assumed, as illustrated in an exemplary equation below.

$$V_{CS}(t) = \frac{\left[(V_o - V_\infty)e^{-t/\tau_{DC}} + V_\infty\right]}{\left(\varepsilon_r^o - \varepsilon_r^\infty\right)e^{-t/\tau_P} + \varepsilon_r^\infty\ ;},$$

Where the polarization current not only influences the resistivity measurements, it can take weeks to fully decay.

This takes into account the changing dielectric properties as the polymer molecules reorient within the material in the influence of an electric field. Decay time is no longer simply counting bits of charge, but must be viewed as a part of a larger behavioral pattern. Developing a promising mathematical model has been due to ability to perform experiments with more sensitivity and flexibility than were previously available. The charge storage method is capable of measuring resistivities of two to four magnitudes greater than the ASTM method.

It is critical for reliable spacecraft charging models to determine appropriate values of resistivity for typical thin film insulating materials as well as the charge storage decay times and processes for the materials. Continued pursuit and development of the charge storage method promises not only significant improvement in data collection for use in designing and utilizing insulator material, it is also a step closer to understanding the fundamental workings within the material itself.

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