Measurement of Conductivity and Charge Storage in Insulators Related to Spacecraft Charging

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35-WORD ABSTRACT:

Novel methods have been developed to measure conductivity and charge storage in thin film insulating spacecraft materials. For a variety of such samples, these values differ by up to 10^4 from current standard values.

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INTRODUCTION

Standard documents for mitigation of spacecraft charging problems advise that the use of slightly conductive insulators is preferred and that highly insulating materials should be avoided in any spacecraft where the radiation level, or the space plasma intensity, is elevated [1,2]. But nearly every common spacecraft insulator currently in use is highly insulating. It is correctly assumed that sufficient conductance of such materials would prevent the development of large electric fields internal to the material and thereby prevent electrostatic discharge pulses that might disrupt the spacecraft. However, it is difficult to find valid measurements for the conductivity of insulating materials during service in the space environment. This paper discusses recent improvements in the methodology for measurements of conduction and electric fields in insulating materials.

In order to avoid spacecraft charging problems in insulators, the motions of conducting electrons and holes must be sufficient to prevent the development of very large electric fields. Problems begin to occur when the field strength exceeds 10^5 V/cm in spacecraft insulators. Therefore, one needs to demonstrate sufficient conducting particle motions at fields $<10^5$ V/cm. Ohm's law is not sufficient in this case. Approximate knowledge of the electric fields developed in the insulators is important. One must consider generation of mobile electrons and holes, their trapping, thermal detrapping, mobility and recombination.

Recently [3], improved measurements designed for spacecraft conditions found that conduction in polyimides was reduced by a factor of 1000 relative to the conduction tabulated in standard handbooks and measured by classical means using electrodes and high voltage power supplies [4]. Classical methods fail to measure the movement of charge within tens of minutes after application of the electric field. Over tens of minutes the dielectric constant increases with time. Under constant voltage, an increasing dielectric constant produces a polarization current that is often misinterpreted as a conduction current. Conductivity values tabulated in handbooks are suspect for this reason.

A primary component of the methods described in this paper is the long time duration over which the measurements are performed. In addition, we considered, sample sizes, voltage levels, electric fields strengths, spacecraft materials, and the space environment including charged particle radiations, plasma and sunlight. In this paper we concentrate on interpretation of the measurements estimate the motions of conducting particles and the relaxation of high electric fields. It is by experimental verification of these two aspects that spacecraft charging problems can be prevented.

FUNDAMENTAL CONSIDERATIONS

To prevent electrostatic discharges, the electric field must relax at least as fast as the space environment injects new charge into the insulator. Conductivity testing should be performed at the appropriate level of electric field. The radiation, plasma, temperature and sunlight environments must be considered in order to properly perform the experiments. Because space radiation injects charge into the interior of insulators, generally the highest voltage is achieved internal to the insulator. This is very different from conditions for classical conductivity measurements , and must be considered.

It is most convenient to use the measured relaxation time for the determination of conductivity. The relaxation time is equal to the product of the bulk resistivity times the permittivity, $\tau=\rho\cdot\varepsilon$. Since the permittivities of nearly all spacecraft insulators lie within a narrow range of values, by measuring the relaxation time we obtain an adequate measure of the bulk resistivity. For most spacecraft environments it requires at least one day exposure to accumulate enough charge in the insulator to develop threatening electric fields, and in some environments months to years of exposure would be necessary to threaten the spacecraft. Therefore, one must be able to measure relaxation time constants from hours to many months.

EXPERIMENTAL APPARATUS

Figure 1 shows the generic spacecraft insulator problem simulated in a vacuum chamber. By placing many insulators on a carousel (not shown in the figure) each insulator may be rotated into a position where an exposure to a specific component of the space environment is provided, or where a current or voltage in the sample can be measured. In this way many insulators may be subjected to a variety of environments and electrical measurements for days to months without breaking vacuum.

So far, our chamber contains a flood electron gun from 0 to 75 keV, a plasma source with bias capability to a kilovolt, an electron-emitting filament, a light source, a surface voltage electrostatic voltmeter, and temperature probes. The sample electrode can be attached to an oscilloscope, a current monitor, a voltage source or a voltmeter. The grounded grid across the center of the chamber prevents the electric fields developed by the electron gun and the plasma source from affecting the sample.

Sample Capacitance. Figure 2 describes the arrangements for several test procedures. The upper sample is enclosed in a grounded metal can so that environmental components will not arrive at the back of the sample. This arrangement is used to evaluate simple conduction through the sample to its electrode. Typically, ±10 to 1000 volts may be applied to attract cold electrons, protons, or ions to the insulator surface. The insulating pad prevents drift of such particles around the sample to the rear electrode. By slowly raising the applied voltage as the insulator is being charged, the energy of the arriving particles can be kept below 10 eV in order to prevent kinetic penetration by the particles. An ammeter at the electrode measures current and total charge arriving at the sample. Assuming the charge remains at the surface, by measuring the voltage at the front surface and relating it to the total charge one determines the sample capacitance from $CV=Q$. The upper straight line in Fig. 3 shows an experimental determination of the capacitance of a good (non-leaking) insulator, and the curved line indicates a leaky insulator.

Simple Conductivity. There are two methods to determine whether or not the charge remains at the front surface, or leaks into the sample, can be determined. First, one may charge the sample with a number of small charge applications by briefly energizing the electron filament, and measuring the resulting incremental sample voltage increase. If charge is penetrating to deeper depths, as time goes on the incremental voltage change per unit charge

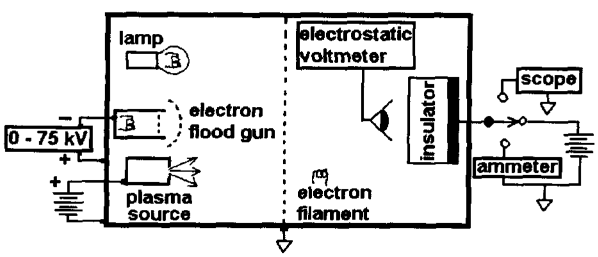

Fig. 1:. Depiction of an insulator sample that may alternately be exposed to various environments and electrical measurements

addition will decrease. The curved line in Fig. 3 is an example of a leaky insulator. Its capacitance may be determined from the slope of the curve at small Q. If charge is remaining on the surface, as time goes on the incremental voltage change per unit charge addition will remain constant as shown by the straight line in Fig 3. Alternatively, one may charge the sample and then monitor the surface voltage versus time afterwards. If the surface voltage decays, then charge is leaking through the sample. Because of the manner in which voltage is applied to the sample, there will be no charge escaping into the vacuum (assuming that the opposite polarity charge can not be emitted) and all currents remain entirely inside the insulator.

Light-induced Conductivity. Having charged the sample in the simple leakage experiment above, one can measure the effect of light upon conduction through the insulator. The enclosed lamp in Fig. 1 illuminates the sample; decay of surface voltage is monitored over time while maintaining the battery voltage so that electrons will not escape the surface of the sample.

Light-induced Emission. Having performed the two prior conductivity tests, emission of charged particles from the sample surface may now be evaluated. The sample electrode is grounded and the sample then illuminated. Two currents will flow acting to reduce the sample surface voltage, one through the sample (conduction) and the other emitted from the sample surface. The light-induced conductivity current (determined in the test above) is subtracted from the total current to obtain the emitted current. For example, a 1-W light bulb will induce significant currents in precharged polyimides.

High-Energy Electron Beam Tests. Charging induced by high-energy electrons is a key consideration for spacecraft charging. Such testing is best performed using the open sample mount in Fig. 2, that allows for more straightforward modeling.. In the closed mount the insulator pads, and the close proximity of the grounded can, will produce unwanted local electric field effects upon the sample. One might wish to place a collimator before the sample, but well spaced from it, to prevent irradiation at the edges of the sample.

When charge resides only on the sample surface the electric field everywhere in the sample is of one polarity. When charge is injected by high-energy particles, the electric field reverses polarity somewhere within the penetration-depth of the particles. This means that conduction currents will flow in one direction near the sample electrode, and will flow in the opposite direction near the sample surface. Therefore, care is required in order to evaluate conduction using electron beam tests. For example, the sample surface voltage is often observed to continue to become more negative even after the electron beam is stopped.

Surface Voltage Measurement After Electron Beam Charging. Figure 1 shows an electrostatic voltmeter residing within the vacuum chamber. Extended electron beam radiation severely affects the voltmeter, often driving it off scale. The open arrangement shown in Fig. 2 is preferable, for at least two reasons. For voltage measurements, we instead use a metal sensor plate placed adjacent to the charged surface and connected to another plate (field plate) outside the chamber. The electrostatic voltmeter senses the voltage developed on the field plate and sensor plate. Because of the capacitance, C_f, of these plates to ground, there is a capacitor voltage-dividing effect with this arrangement, typically lowering the sensitivity of the probe by a factor of two to six. With this arrangement the electron beam cannot harm the electrostatic voltage probe. If the probe breaks during the month-long experiment it may be repaired without opening vacuum, thus saving the data.

The second reason for preferring the sensor field plate arrangement relates to electron emission from the insulator. Electron beam charging of the samples produces an electric field at the surface of the sample that drives electrons out of the surface and across the vacuum. The sensor plate will collect these electrons thus developing negative voltage on the sensor field plate arrangement. Knowing the capacitance, C_f, the

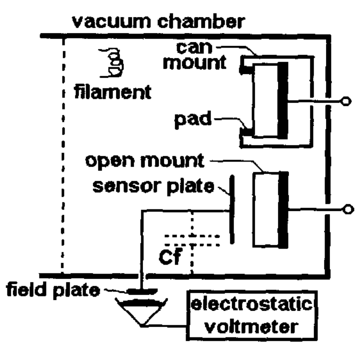

Fig. 2:. The floating voltmeter, and two sample mounts: open and covered.

rate of voltage change on the sensor field plate allows us to determine the electron currents leaving the sample surface. Alternatively one may monitor the current flowing from ground to the sample electrode in order to measure the electrons emitted across the vacuum, but it is a small, noisy current making measurement difficult. Table 1 indicates such a measurement. Instead, monitoring the rise of voltage on C_f provides a very quiet signal.

Sample Leakage During and After Electron Beam. Figure 4 shows electron beam *Q-V* charging data taken in the open mount. *Q* is the total charge incident on the sample and its electrode, and *V* is the surface voltage. The curvature of the line indicates conduction currents during the time of irradiation; other different samples exhibit more or less curvature.

After irradiation, the surface voltage can be monitored for decay due to both conduction through the insulator and emission from the insulator surface. One can monitor the emission currents by measuring the collection of electrons on the sensor field plate along with knowledge of C_f. This is accomplished as follows. First, one establishes a zero reading when the sensor field plate faces ground. Next, the sample is rotated before the sensor and held there for a period of time, *t*. Its reading will change both because current is emitted to the sensor field plate and because the sample voltage is decaying. After the sensor field plate has collected charge, it is again faced to ground and its new "ground" voltage reading shows how much charge was absorbed during time *t*.

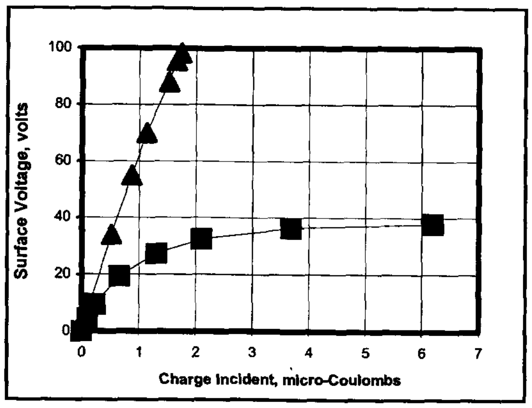

Fig. 3:. Sample voltage vs. incident charge from the electron filament that was attracted to the sample surface by +100 V on the rear electrode.

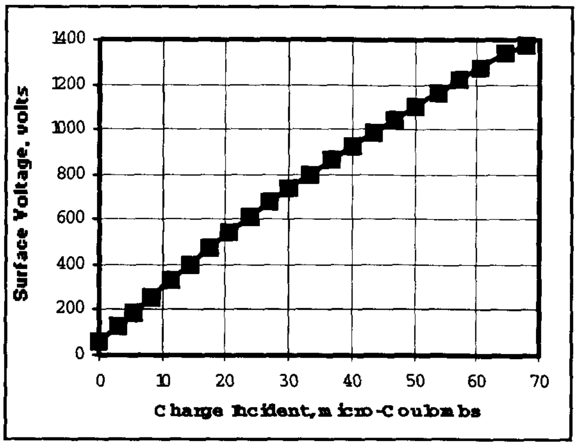

Fig. 4:. Charging of a 31 cm^2 silicate glass sample by 10 keV electrons.

By also knowing the capacitance of the sample, one may calculate the component of its surface voltage decay due to emission of electrons to the sensor plate. Multiple measurements of the decay of surface voltage, each performed rapidly so that negligible charge is delivered to the sensor plate, provides information about the total loss of charge from the sample. Subtracting the emitted charge from the total charge loss provides the charge conducted through the sample to the grounded electrode.

The data in Table 1 indicate that a substantial portion of the decay of surface voltage is by emission of electrons into the vacuum. To our knowledge, this is a novel testing capability that provides important information. While penetrating into the insulator, the high-energy electrons excite electrons and holes into trapping states and into mobile states located between the sample surface and the maximum depth of penetration. Such conducting species provide the charge to be later emitted from the surface. No such species are introduced beyond the high-energy electron penetration depth and therefore smaller conduction and charge removal can proceed through the deeper un-irradiated portion of the insulator.

SUMMARY

Handbook values of conduction in insulators are inappropriate for spacecraft charging applications, too

Table 1. Currents emitted from the surface after being charged to –1712V.

Time After Charging,(min)	Current,(nA)
5	0.07 - noisy
65	0.02 - quiet
Average of 60-min interval	0.05

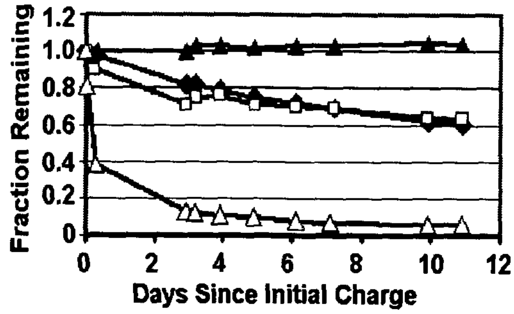

Fig. 5:. Surface voltage decay for three silicate glass samples and one FR4 PC board sample (lower).

large by factors up to 10^4 due to flawed methods of interpretation [3,4]. We have measured this to be true in polyimides, Mylar, glass, Teflon, and three kinds of circuit board material. Figure 5 shows surface voltage decay rates for four spacecraft insulators. In this paper we have developed techniques for the measurement of conductivity in practical insulator materials that are applicable for the space environment. Further, we have developed techniques that distinguish amongst various charging and conduction mechanisms so that better predictions can be made for spacecraft. For example, the conductivity contributed by secondary electron and hole production by the radiation may be evaluated separately from the natural conductivity of the samples. In some samples the effects of visible light-induced conductivity are dominant while in other samples visible light provides no additional conductivity. Charge leakage should be measured on timescales reasonably similar to that experienced in space, and the apparatus described here is designed to do this reliably.

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