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

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Abstract*-- Improved experimental methods are discussed for laboratory measurement of conductivity and electric field in insulating spacecraft material intended for space radiation and plasma environments. These measurement techniques investigate the following features: 1) Measurements of conductivity are up to four orders of magnitude smaller than those determined by existing standard methods. 2) Conductivity is altered as radiation accumulates and trapping states fill with electrons. 3) With intense keV electron irradiation, electrons are continually emitted for hours from the irradiated surface after the irradiation ceases. 4) Charging induced by electron irradiation is strongly modified by the electron-hole pairs that the irradiation generates in the insulator. 5) High field effects at 10^6 V/cm act strongly on the electron-hole pairs and on electrons in shallow traps to provide extended conductivity. 6) The capacitance of the sample can be measured in the same apparatus along with the other testing. 7) Visible light can be used to investigate conduction by electrons (or holes) emitted from shallow trapping levels. The qualitative physics of such processes in solid dielectrics has long been known, and instrumentation is developed here for measuring the effects in practical spacecraft charging applications.

I. Introduction

NASA Handbook 4002, NASA Technical Paper 2361, and other documents for spacecraft design advise that the use of slightly conductive insulators is preferred to mitigate spacecraft charging problems [1]-[2]. Highly insulating materials should be avoided in spacecraft charging environments. 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 them from developing electrostatic discharge pulses. However it is difficult to find valid measurements for the conductivity of insulating materials during service in the space environment. This paper discusses improvements in the methodology for measuring conduction and electric fields in insulating materials. The measured data in this paper serve only to assess the instrumentation and experimental methods, and should not be used to qualify the samples.

Ohms law provides a common perspective for predicting particle currents in spacecraft insulators, but it is not sufficient. Instead, one must consider the generation of mobile electrons and holes, their trapping, thermal de-trapping, mobility and recombination. Determination of the motions of electrons and holes is difficult in semiconductors and is more difficult in insulators. In order to prevent spacecraft charging problems in insulators one needs to show that the motions of conducting electrons and holes are sufficient to prevent the development of very large electric fields in the insulators.

Insulator discharge pulsing begins to occur when the field strength in insulators exceeds $1x10^5$ V/cm. At larger field strength, carrier motion is field dependent, difficult to model, and may further assist in producing electrical breakdown. Therefore, in order to reliably prevent spacecraft charging problems, one needs to demonstrate sufficient conducting particle motions at fields less than $1x10^5$ V/cm. When measuring conduction currents in insulators, knowledge of the electric fields developed in the insulators is needed.

Given enough time in the absence of conduction, the accumulation of high-energy charged particles stopped in the insulators will ultimately produce pulsed discharges, no matter how well shielded. To prevent the occurrence of pulsed discharges the conduction currents must remove charge as fast as it is deposited by the radiation while holding electric field strength below $1x10^5$ V/cm.

A. Classical Methods

In a recent paper [3], earlier measurements found that conduction in polyimides was lower by a factor of 10^4 relative to the conduction measured by classical means and tabulated in handbooks. [4] The classical methods fail to measure conduction beyond tens of minutes after application of an electric field. During time durations of tens of minutes, in addition to motion of charges, the dielectric constant increases as internal polarization increases over time. With the classical application of constant voltage, a current due to changing polarization may be misinterpreted as a conduction current. Resistivity or conductivity values tabulated in handbooks are suspect for this reason. Additionally the application of metal electrodes to both sides of the dielectric provides two interfaces at which additional charge injection and molecular polarization may also provide false current

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measurements over a short time scale.

For example, consider the parallel-plate capacitor under constant voltage as used in the classical test procedure shown in Fig. 1. In the classical test the charged particle current inside the insulator per unit area, **J**, is given by **J=E**/ρ where **E** is the electric field in volts/cm and ρ is the resistivity in ohm-cm. The test procedure assumes that I is the current over the entire sample area.

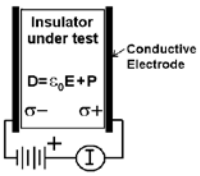

Figure 1. Classical Test Circuit for Measurement of Resistivity. The sample is shown in cross section and the heavy lines are the conducting electrodes. The charge per unit area on the electrodes, σ, is provided by the battery.

However, the meter current is, in truth, the current flowing in the wires and is composed of the charge particle current through the insulator plus the net rate of change of the image surface charges, dσ/dt, on the electrodes that are produced by the battery. The image charge currents are derived as follows. The voltage, V, is constant and produces a constant electric field, **E**, given by [5].

$$V = \int_0^a \vec{E} \cdot \vec{dx}.$$

Here we assume the sample to have thickness a, and continue the derivation assuming an isotropic homogeneous sample where **E** is uniform and perpendicular to the plates and parallel to the dielectric polarization vector, **P,** and the image charges, σ, on the plates are of equal magnitude and opposite sign. Using Maxwell's integral equation for the electric displacement vector, **D**, produced by surface charges, Q, on "1-D planar" sample with electrodes,

$$\oint \vec{D} \cdot \vec{ds} = Q \ ,$$

we find

$$\vec{D} = \sigma \vec{x} = \varepsilon_0 \vec{E} + \vec{P} \ ,$$

where σ is the magnitude of charge per unit area on one plate, $\vec{x}$ is a unit vector, and ε_0 is the permittivity of vacuum.

Therefore, in order to hold the voltage constant the battery must deliver image charge current, $\mathbf{J_i}$, through the meter and to the electrode according to

$$\vec{J}_i = \frac{d}{dt}\left(\sigma \vec{x}\right) = \frac{d}{dt}\left(\varepsilon_0 \vec{E} + \vec{P}\right) = \frac{d}{dt}\vec{P}.$$

With constant voltage applied, the total current through the meter is therefore composed of charge currents, $\mathbf{J_c}$, plus polarization image currents, $\mathbf{J_i}$. This is a well-known phenomenon.

As the polarization, **P**, changes while constant voltage is applied there is a current in the meter. In addition to the time-dependent polarization, there will be a time-dependent injection of charge at the metal plate-insulator interface, a solid electrochemical junction of two materials. There may also be injection of ions into the insulator by chemical activity at the junction. The mobile ions will drift under the influence of electric field setting up a gradient in their density that ultimately produces a Ficks-Law diffusion current to counter their drift current. Thus at least three components of current are not considered in the standard resistivity measurement technique.

The current associated with an increasing polarization cannot proceed forever. After some time, all of the polar molecules will have transitioned to full polarization and additional polarization will not occur. Similarly, injection of ions may slow if they become trapped near the electrodes and "repel" further injection. Electron and hole injection may slow down as the junction field is developed under conditions of slow trapping build-up. The classical method performed over very long time-duration finds that the current decays well beyond that at the classical time duration of ten minutes. We have found, and it is frequently commented in the literature, that the current continues to decay for a day, or more, with test conditions of Fig. 1.

Two samples of polyimide were measured using both the classical method and the surface voltage decay method [3] in order to compare the methods. The classically measured currents and resistivities in Table 1 were determined using plus and minus 64 volts on the 16.6 cm^2 central electrode (central electrode was surrounded by a guard ring) on the 0.051 mm thick samples (10^4 V/cm). The surface voltage decay method found the resistivities to be several orders of magnitude larger in the same samples [3].

Table 1. Classical Measurements on Two Polyimide Samples.

TIME AT BIAS	SI001 polyimide	KA001 polyimide
2 minutes	0.060 nA	0.14 nA
6 minutes	0.030 nA	0.11 nA
10 minutes	0.023 nA, ρ = 0.88E16 ohm-cm	0.091 nA, ρ = 0.23E16 ohm-cm
4 hours	0.010 nA, ρ = 2.0E16 ohm-cm	
7 hours	0.011 nA, ρ = 1.8E16 ohm-cm	
43 hours		0.057 nA, ρ = 0.37E16 ohm-cm
123 hours	0.0076 nA, ρ = 2.7E16 ohm-cm	

Well beyond those in [3] the experimental methods have been developed in consideration of the time durations, sample sizes, voltage levels, electric fields strengths, spacecraft device structures and materials, and the space environment including charged particle radiation, plasma and sunlight. Primary components of the new methods are the long time duration over which the measurements are performed, taking the measurements under constant charge instead of constant voltage, measurement of static surface voltage using capacitive coupling, controlled sequencing of sample treatments, inter-comparison of multiple samples, and diverse sample treatments without breaking vacuum. Features 2-6 in the abstract are new in this work and are enabled by the new apparatus.

In the new methods, results are interpreted in order to estimate the in-space generation of electric fields and the relaxation of high electric fields. The voltages developed in space are generated by impressing charge into the insulation, not by the application of voltage from a power supply onto electrodes. By experimental verification of the motions of conducting particles, and the resulting relaxation of electric fields, spacecraft charging problems may be predicted and prevented. The effects of time dependent polarization and ion injection may also be considered when using the new methods.

B. Considerations for Spacecraft Applications.

It is desirable to demonstrate that electrostatic discharge will not occur in the insulator and therefore it must be demonstrated that the electric fields will be less than 1×10^5 V/cm in the insulators in space. The conductivity testing should be performed at the appropriate level of electric field, near or below 1×10^5 V/cm, and the electric field relaxation rate must be determined relative to the charge injection rate by the space environment. Radiation, plasma, temperature and sunlight environments must be considered.

Because space radiation injects charge into the interior of the insulator, generally the highest voltage is achieved internal to the insulator. This is different from the conditions for classical measurements of conductivity, and must be considered when interpreting the data.

For measurements of average conductivity it is most convenient to use the relaxation time for the determination of conductivity, or conduction currents, in the sample. After charging the sample and then turning off the charging process, the Relaxation Time, τ, is the time it takes for the electric field to drop to 1/e of its initial value. For an ideal dielectric τ is equal to the product of the bulk resistivity, ρ, times the permittivity, $\kappa\varepsilon_0$,

$\tau = \rho\kappa\varepsilon_0$.

(κ is the relative dielectric constant). Since κ of nearly all spacecraft insulators lie within a narrow range, 2-10, and is usually well known, by measuring the relaxation time we obtain an adequate measure of the bulk resistivity. For most spacecraft environments it requires at least one-day of 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 the measurements must be capable of measuring relaxation time constants from hours to many months. Although we know the samples will have a range of dielectric constants throughout the bulk for several reasons, we assume an average time constant is adequate for our purposes.

With electric fields of order 10^5 V/cm, and insulator thickness of microns to millimeters, and radiations capable of penetrating up to several mm, the measurements must be capable of evaluating voltages from tens of volts to tens of kilovolts. Typical insulators capable of storing enough electrostatic energy to be threatening have at least one dimension exceeding one mm. The apparatus discussed in this paper evaluates materials of large sizes that provide the largest threats. Examples are thermal blankets, circuit boards, wire insulation, connectors, IC plastic packages, and optical windows. Integrated circuit passivation, being thin, will not be highly-charged by the space radiation environment. Small insulators such as a dab of epoxy can produce only small electrostatic discharges, so they need to be evaluated only for special purposes.

Both electrical testing and evaluation require the use of Maxwell's equations and therefore a complete equivalent circuit must be established for the experiments. Most often the experiments place one metal electrode on part of the surface of the sample. The arrangement of electrodes may have a profound effect on interpretation of the experiment for comparison with the real spacecraft arrangement.

~~I.~~II. EXPERIMENTAL APPARATUS AND CONDUCTION MODELING

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Figure 2 describes the generic spacecraft insulator problem, and places the insulator in a simulation chamber for testing. 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, usually one at a time, may be subjected to a variety of environments and electrical measurements over a period of days to months without breaking vacuum.

The chamber contains a broad-beam electron gun with accelerating potentials from 0 to 75 keV, a plasma source with bias capability, an electron-emitting filament, a light source, a sample surface voltage-sensing device, 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 electric fields developed by the electron gun and the plasma source from affecting the sample. Each feature of the apparatus is discussed below in concert with the measurement results.

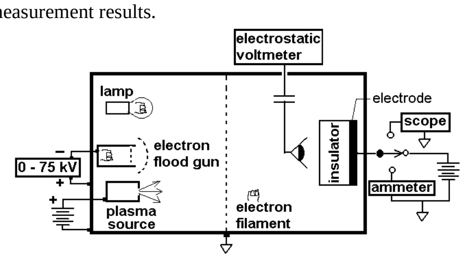

Figure 2. The test chamber can alternately expose samples to various environments and electrical measurements. Often, only one conductive electrode is applied for such testing.

Several phenomena related to charging and the conductivity of insulators have been investigated using the apparatus. This work serves to introduce the utility of the apparatus for measurement of charge storage and conductivity. The relevant phenomena are only briefly introduced in order to describe the measurement techniques.

~~B.~~A. Sample Conditions and Calibration of the Voltmeter

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The electrostatic voltmeter in Fig. 2 must be empirically calibrated for each sample. This is simple for thin samples where the voltage drop through the thin sample is small. Place the voltmeter sensor before the sample henceforth always measuring the sample surface voltage from this position only. Apply a known voltage to the rear sample electrode and set the electrostatic voltmeter to this voltage reading. It is now calibrated under the assumption that the voltage drop through the sample is negligible. For thick samples one places a biased metal foil temporarily on the surface to calibrate the voltmeter.

B. Surface Voltage Probes

Figures 2 and 3 show an electrostatic voltmeter that measures sample surface voltage. When this was mounted directly inside the vacuum chamber facing the sample, extended electron beam exposure drove it off scale. For most testing we prefer the external mounting arrangement shown in Fig. 3, for three reasons. Here, a sensor plate of metal is remotely moved adjacent to the charged sample surface and connects to another plate (field plate) outside the chamber. The electrostatic voltmeter, in air outside the chamber, senses the voltage developed on the field plate and sensor plate. Because of the capacitance, Cf, 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. The electron beam charging produces such high voltages that the voltage division is probably more helpful than hindering.

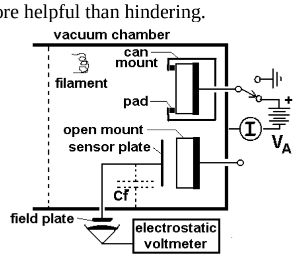

Figure 3. Two Methods for Sample Mountings and Measurements.

The first advantage of the external mounting is that the electrostatic voltage probe will not be harmed by the electron beam. Second, if the probe breaks during a typical month-long experiment it may be repaired without opening vacuum thus saving the data in the samples. Third, a time dependent increase of voltage on the sensor plate is a sensitive indicator of charge emitted by the sample, a valuable added benefit.

~~B.~~C. Measuring Sample Capacitance

Knowledge of the sample capacitance is essential in order to interpret many of the measurements. Figure 3 describes the arrangements for several of the test procedures. The uppermost sample is enclosed in a grounded closed metal can so that environmental components such as plasma cannot arrive at the back or sides of the sample. Currents flow only to the surface of the sample. This arrangement is used to evaluate capacitance and simple conduction from the surface of the sample to its rear electrode. Typically 10 to 1000 volts (V_A) may be applied to attract cold electrons or protons or ions through the vacuum to the insulator surface. The insulating pad in Fig. 3 prevents drift of such particles around the sample to the rear electrode (yet it adds another insulator to the system to be considered). By slowly raising the applied voltage as the sample insulator is being charged the energy of the arriving particles can be kept as low as10 eV in order to prevent kinetic penetration by the particles. The ammeter, I, measures the current and the total charge arriving at the sample surface. Assuming the charge remains at the surface, by measuring the voltage at the front surface when the switch is grounded and relating it to the total charge delivered to the sample, one determines the sample capacitance. For the small currents normally encountered in this application, it is helpful to use a charge integrating current meter to average-out noise.

The straight-line trace in Fig. 4 shows an experimental determination of the capacitance of a good (non-leaking) insulator in the closed can mount.

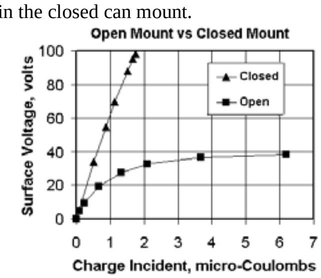

Figure 4. Capacitance measurements in two identical samples with one sample mounted in the closed can, and the second sample mounted in the open configuration where electrons can drift to the rear of the sample through the vacuum.

For clarity of measurement, one must be careful that the capacitance from the front to the rear of the sample is large compared to the capacitance from the sample surface to both the chamber walls and the can. If the charge delivered to the sample is Q, if the capacitance of the sample is C_S and if the capacitance of the surface to the wall and can is C_W, then the charge measured by the integrating ammeter, Q_M , will be $Q_M = \dfrac{C_S}{C_S + C_W} Q$. It is not easy to determine C_W.

~~B.~~D. Electron Beam Testing

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The in-space charging is most commonly due to high-energy electrons. Testing with high-energy electrons is best performed using the open sample mount in Fig. 3. In the closed mount the insulator pads as well as the close proximity of the grounded can will produce difficult local electric field effects upon the sample. The open configuration allows for more straightforward modeling, but some of the irradiation electron current may flow directly to the sample electrode. One might wish to place a collimator before the sample, but spaced from it, to minimize irradiation current at the edges and at the electrode of the sample.

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The complications related to control of the incident beam current, secondary and backscattered electron emission, and their dependence on the sample surface voltage will not be discussed here, but are sometimes important. As the sample charges, the incoming electrons are deflected to non-normal incidence so that the secondary and backscatter yields increase more than that which would occur due to simple slowing of the incident electrons. In some measurement techniques these effects are important but difficult to control.

Figure 5 is a qualitative picture that compares the electric field profile developed by charge on the sample surface with the electric field profile developed by charge injected by high-energy electrons. When charge resides only on the surface the electric field everywhere in the ideal insulator is a constant. When charge is injected by high-energy particles the electric field reverses polarity at the zero-field plane somewhere within the penetration-depth of the particles. For the two cases shown, the zero-field plane lies exactly on the surface in the surface charged case, and at about 1/3 depth into the sample in the e-beam charged case. 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 as shown in Fig 6. Therefore care is required in order to evaluate conduction using electron beam tests. For example, there is a common situation whereby the sample surface voltage slowly becomes more negative after the electron beam is stopped [6].

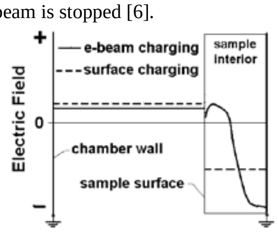

Figure 5. Electric Field Profiles Produced by Electrons on the Surface (dashed line) and by Electrons Injected by Electron Beams that Penetrate About Half-way Into the Insulator (solid line). Since the charge in the vacuum is negligible, the vacuum electric field is constant throughout the vacuum in this 1-D geometry. The electron beam induces positive charge near the sample surface by generating both secondary electrons and delta rays.

Figure 5 is for a situation where the thickness of the sample is about 1/3 of the thickness of the vacuum, and therefore the electric field in the vacuum is roughly 1/3 of that in the sample with surface charge only. In real spacecraft arrangements, the distance to ground in the vacuum is very much greater than the sample thickness. Thus, in real spacecraft, the electric field strength in the back of the insulator is perhaps a hundred times larger than that in the front.

A large variety of conduction effects occur in keV-electron irradiated samples making interpretation of data complex. Figures 5-7 provide a simplified point of view to describe conduction effects in keV electron-irradiated samples. At the depth of the zero-field plane the voltage is most negative [7]. From this plane the distance to the sample electrode is short and therefore the electric field near the electrode is large. This field in the back of the sample can become so large that shallow-trapped electrons tunnel to the conduction band (Fig. 7) and provide enhanced conductivity. This can occur in a range of field strength similar to that in which electrical breakdown *easily* occurs (>5x10^{5} V/cm), and may either contribute to breakdowns or prevent them depending on the nature of the defects that are responsible for the breakdowns.

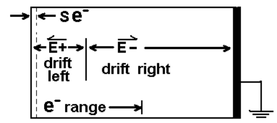

Figure 6. There is a zero-field plane such that conduction electrons drift leftward on one side, and rightward on the other side of the plane. Usually, the zero-field plane lies between the penetration range of the keV electrons and the region from which secondary electrons (se^{-}) are emitted.

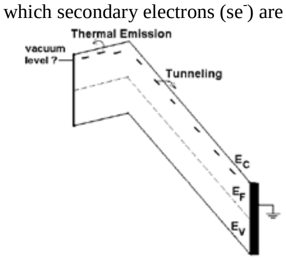

Figure 7. Simplified Band Diagram for Electric Field Effects on Conduction in Samples Previously Irradiated by keV Electrons. Charged insulators have emitted electrons for hours after cessation of irradiation indicating that the conduction band is not significantly below the vacuum level.

Thermal emission from shallow traps occurs (slowly) everywhere that shallow traps are occupied. The distance from the zero-field plane, where the voltage is maximum, through the sample free surface and across the vacuum is large, and therefore the electric field in this region is small. In this region trapped charge must be thermally emitted to contribute to conduction, typically a small effect at room temperature. However, the keV electrons pass through this region and during their passage excite roughly 40 conduction electrons and holes for each keV of energy deposited, thereby providing significant conductivity to mitigate the development of extreme fields in this region. After the irradiation stops, the tunneling currents and thermal emission currents may persist until shallow traps have emptied.

Light can be utilized to study the trap populations after charging the sample. The fundamental principle behind such a study, depicted in Fig. 8, is that light of wavelength λ can excite an electron transition from a trap level into the conduction band provided that $hc/\lambda > \delta E$ where h is Planck's constant, c is the speed of light, δE is the energy separation from the trap to the conduction band. The keV electron irradiations excite electrons into the conduction band from where they may decay into traps. After irradiation, one can probe the trap population by exciting these trapped electrons into the conduction band so that the sample surface voltage decays.

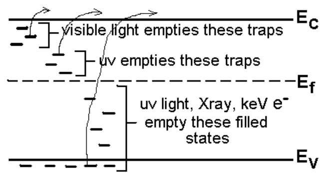

Figure 8. Electron Transitions in Insulators Excited by Light of Various Wavelengths. In typical insulators 10eV>E_C –E_V>5eV.

Interpretation of electron beam tests will be based on the concepts in Figs 5-8. Such concepts have been developed by many people over many years and it is difficult to credit original works. For background reading see [8]-[11].

~~I.~~III. MEASUREMENT TECHNIQUES AND RESULTS

~~B.~~A. Measuring Simple Leakage and Capacitance

To evaluate conduction in unaltered insulators their surfaces must be charged with low-energy electrons or ions. KeV electron beams or ions alter the sample as they excite secondary processes that repopulate trapping states in the insulator, or otherwise alter the material. Whether the charge remains at the front surface, or leaks into the sample, can be determined using one of two methods.

The first method indicates that leakage occurs, but provides only approximate measurements of the leakage current. The sample is charged using the capacitance method discussed above with a number of brief charging applications by repeatedly lighting the electron filament, and measuring the incremental voltage increase after each filament lighting. If charge is penetrating to deeper depths, as time goes on the incremental voltage change per unit charge addition will decrease. The slight curvature of the trace in Fig. 9 is indicative of a slightly leaky insulator. The insulator's capacitance may be determined from the slope of the curve at small Q.

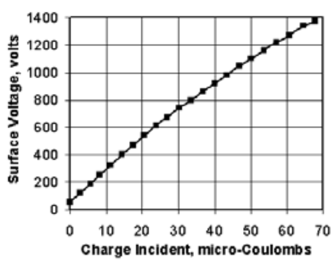

Figure 9. Ten-keV Charging Curve for Slightly Leaky Sample of 0.5 mil Glass.

In the second method one charges the sample and then monitors the surface voltage as a function of time. If the negative surface voltage decays then charge is leaking through the sample or across the vacuum. Electron flow from the sample across the vacuum can be prevented by applying positive voltage on the rear of the sample sufficient to keep the surface at a small positive voltage.

B. Measuring Light-induced Conduction

Having charged the sample in the simple leakage experiment above, one can measure the effect of light upon conduction in the sample. Simply turn on a filament to illuminate the sample and monitor the decay of surface voltage over time. Do this while maintaining minimal positive battery voltage so that charge will not escape the surface of the sample. Also place the filament at a net positive voltage to prevent electrons emitted from the filament or from the walls of the chamber from moving to the insulator surface. The light-induced conductivity will cause the surface voltage to decay, and this voltage decay is a sensitive monitor for conductivity. Note that the current through the wire connecting the sample electrode to ground will be very small, much less than the current in the sample, and is not a sensitive measure of the conduction current. The decay of surface voltage is, however, a sensitive measure of the internal currents.

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A mathematical model for the depth profile of light-induced conductivity is required to relate the surface voltage-decay to an exact quantitative estimate of the conductivity. Such models are beyond the scope of this paper. For spacecraft, however, one often needs only to prove that sunlight will cause conduction to bleed the charge to ground. If a light with intensity less than one sun, and a spectrum colder than the sun, is seen to quickly bleed the charge away, then the conductivity has been adequately characterized for spacecraft purposes.

Polyimide samples 50 microns thick at 1 kV surface voltage were discharged in a few hours by a 1-watt incandescent filament, yet charged Teflon ™ was nearly unaffected. In some samples light can be used to remove internal charging induced in prior tests so that further testing may proceed without initial charge in the sample.

~~B.~~C. Measuring Light-induced Emission

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Having performed the two prior leakage test procedures one may now evaluate the emission of charged particles from the surface of the sample. Ground the electrode of the sample, then illuminate the sample with light. Two currents will flow, one through the sample (leakage) and the other emitted from the sample surface and across the vacuum chamber. The sum of these two currents will reduce the surface voltage of the sample. The leakage current was determined in the previous test described above and may be subtracted from the total current to obtain the emitted current. We have determined that a simple light bulb will induce significant currents in pre-charged polyimides and therefore the light emitted by an electron gun will modify the charging process induced by the gun's electrons.

~~B.~~D. Sample Leakage During and After Electron Beam

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Figures 9,10 show electron beam Q-V charging data for two similar (size, thickness and mounting) glass samples (proprietary undisclosed materials) manufactured by differing processes, the straight line for a sample showing no conductivity, and the curved line for a sample exhibiting conductivity, both taken in the open mount. Q is the total charge incident on the sample surface and V is the surface voltage. The electron beam was at 10 keV where the electrons penetrate and stop less than 10% into the insulator. Currents arriving at the sample surface and the sample electrode were not affected by the developing surface voltage, as demonstrated by the straight line in Fig. 10 for the good insulator. The curvature of the line in Fig. 9 indicates occurrence of conduction currents during the time of charge-up irradiation.

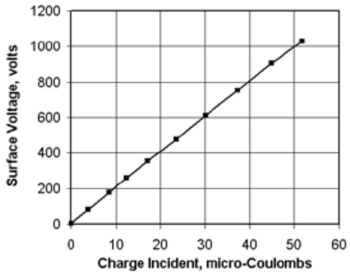

Figure 10. Ten-keV Charging Curve for non-Leaky Sample of 0.5 mil Glass.

Figure 11 is for the same glass samples irradiated with 40 keV electrons where the deepest penetrating electrons penetrate nearly 90% into the sample. Such irradiation produces a situation where: the zero-field plane (see Figs. 6,7) is not far from the electrode, the electric field in the rear of the sample is large, many electrons are excited into traps near the rear electrode, and tunneling currents are large. On these samples with 40-keV beams, much smaller surface voltage is produced than is produced with 10- or 20-keV electron beams even though at all three energies all of the electrons are stopped in the insulator.

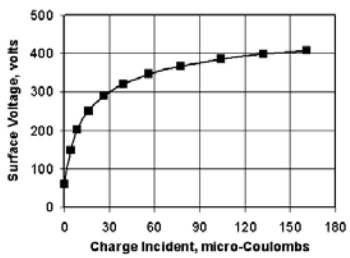

Figure 11. Charging of the 0.5-mil Glass Samples by 40-keV Electrons.

Figure 11 hints that the various radiation-generated conduction mechanisms in these glass samples would prevent the development of a strong electric field provided there is sufficient beam that penetrates throughout the sample.

~~B.~~E. Surface Voltage Leakage After Irradiation

Charge leaking through the sample and/or emitted from its surface causes the surface voltage to decay. Figure 12 shows the fractional loss of surface voltage for three (nominally 0.5 mil thick) silicate glass samples initially charged to about –300 volts, and one (32 mil thick) FR4 circuit board initially charged to about –600 volts. These samples were charged in the simple charging procedure by lighting the filament when +1000 volts was placed on their electrodes. Error bars were nominally 2%. Even though it is relatively leaky, FR4 circuit board is known to produce pulsing in space radiations.

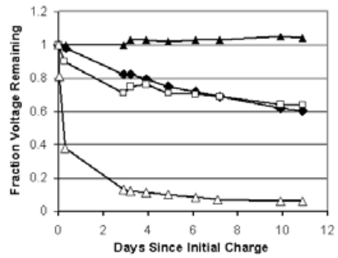

Figure 12. Surface Voltage Decay on Four Samples. The top curve was produced by the glass sample that also produced Fig. 10. The two middle curves were produced by the glass materials in Fig. 9. The bottom curve came from FR4 circuit board.

~~B.~~F. Surface Emission After Irradiation

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After irradiation, the surface voltage was monitored for decay due to both conduction in the insulator and emission from the insulator surface. First, the emission current from the sample was monitored with a current meter between ground and the sample electrode. Table 2 indicates such measured currents from a (approximately 0.5 mil thick) glass sample charged to 1.7 kV with 10-keV electrons. The measurement is actually the total image current from ground to the electrode due to both conduction currents in the sample and electrons emitted across the vacuum. The noise in the measurement could have been generated by either component of the current, the source of the noise is unknown.

Table 2. Currents from ground to the rear electrode as electrons are 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

Second, the emission current was monitored by measuring the collection of electrons on the sensor field plate along with knowledge of capacitance Cf in Fig. 3. A trick is used to measure the charge emitted to the sensor field plate. The sample can be rotated in front of, and then away from, the sensor field plate. 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. The sensor voltage 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 indicates how much charge was absorbed during time t. A typical experiment is shown in Fig. 13. Monitoring the rise of voltage on Cf provides a very quiet clean signal. For example, with this method we have monitored the currents generated from the chamber walls, or from the field plate, by background Earth radiation and cosmic rays.

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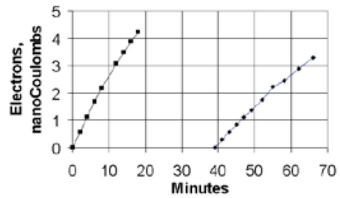

Figure 13. Charging of the Sensor Plate by Electrons Emitted from a Sample after Being Charged to –1100 Volts by 10 keV electrons. After 18 minutes the measurement was discontinued, and started again after 38 minutes. Cf = 35 pF.

By also knowing the capacitance of the sample one may calculate its surface voltage decay due to the emission of the charge onto the sensor field plate. Separate 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 lost provides the measurement of the charge conducted through the sample to the grounded electrode.

~~I.~~IV. SUMMARY

We have developed techniques that distinguish amongst various charging and conduction mechanisms for the measurement of conductivity in practical insulator materials for the space environment. Recently it was shown that handbook values of conduction in insulators are generally in error since they are too large by factors up to 1000 or more due to the flawed methods for earlier data. We have measured this to be true in polyimides, Mylar, silicate glass, Teflon, and three kinds of circuit board material.

The instrumentation and techniques explained here measure: the dielectric relaxation time related to its dark conductivity, the surface voltage after various charging and discharging processes, the currents emitted from the insulator sample, and the current from ground to the sample electrode. Treatments include: charging with low energy (<100 eV) electrons and/or ions, charging with electron beams to 75 keV, exposure to light, and heating/cooling.

Conductivity contributed by secondary electron and hole production by the radiation may be evaluated separately from the natural dark conductivity of the samples. In some samples the effects of visible light-induced conductivity are dominant while in other samples visible light provides negligible conductivity. Charge leakage should be measured on timescales reasonably similar to that experienced in space, at least a month, and the apparatus described here is designed to do this reliably.

The conductivity of a dielectric is altered as radiation accumulates and trapping states are filled with electrons. Evidence for this comes from heavy keV-electron irradiation where electrons are continually emitted for hours from the irradiated surface after the irradiation ceases (Table 2 and Fig. 13). Further evidence is provided in Fig. 11 where, during early irradiation, the sample behaves as a capacitor whereas during continued radiation it behaves as a voltage regulator. High field effects at or above 10^6 V/cm act strongly on the electron-hole pairs and on electrons in shallow traps to provide extended conductivity which can be evaluated by measuring surface voltage on the insulator.

During irradiation the generation of one electron-hole pair for approximately 30 eV lost by the incident keV electrons provides many conducting carriers to "bleed off" the electric field generated by the stopped keV electrons. If these carriers have sufficient mean free path and can access a grounded electrode they will probably prevent extreme charging and frequent pulsed-discharging of the insulator samples from occurring. Monitoring surface voltage while irradiating with electrons that stop just short of penetrating the insulator provides a way to roughly evaluate electron mean free path in an insulating material.

Visible light can easily be used to investigate conduction by electrons (or holes) emitted from shallow trapping levels. This provides a quick pass-fail test for insulators exposed to sunlight. If the insulators lose charge when exposed to incandescent light, they will not charge-up in sunlight. A thin Kapton sheet will not charge in sunlight if its back surface is grounded. For most practical insulators the dark conductivity is insufficient to prevent serious charging but the radiation- and light-induced conductivity may provide significant conductivity. The test procedures described here help to determine the various conduction mechanisms.

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~~I.~~V. REFERENCES

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