Utah State University

DigitalCommons@USU

Senior Theses and Projects | Materials Physics

2-21-2005

Classical Resistivity Method in Atmosphere and Vacuum

Shigeyuki Takahashi

Utah State University
Physics Department Seminar

Classical Resistivity Method in Atmosphere and Vacuum

Senior Research Project 4900

Shigeyuki Takahashi
Utah State University
Department of Physics

Abstract

In the space industry one of the most serious problems is charge storage on spacecrafts caused by plasma, solar-photo-emission that causes damage to the spacecrafts. Therefore, the research by government and industry about spacecraft charging is thriving because there are still plenty of unknown faces in the space. A key first step for research of the phenomenon in ground-based laboratory test is to know well the most suitable experimental methods for measuring resistivity of spacecraft materials.

This talk describes my investigations of the Classical Resistivity (constant voltage capacitor) Method to measure resistivity. I concentrate on understanding the differences between tests done in atmosphere and vacuum.

Thursday, February 21, 2005
12:00 noon

CASS/PHYSICS CONFERENCE ROOM
SER 244

Senior Project Report

Classical Resistivity Method in Atmosphere and vacuum

Shigeyuki Takahashi

Department of Physics in Utah State University

May 2, 2005

Introduction

Charge Resistivity Method, which is most common method for measuring resistivity of highly insulating materials (ASTM 257.) The highly insulating materials are usually very thin film, typically 25μm that is provided by NASA. This method measures the resistivity of the insulators materials with using a capacitor. The resistivity is calculated with the thickness of the insulators materials, size of capacitor, amount of voltage supplied, amount of current flowing in this system, and so on.

In this experiment, the resistivity of an insulator material (Kapton/Aluminum thin film) was measured in two different environments (atmosphere and vacuum.) After plenty of measurement of the resistivity in the two different environments, we compared the data in atmosphere with vacuum to see the difference. In this examination, it was learned the limitation of this Classical Resistivity Method, and was observed significant difference in them.

In the analysis of the different data result, it realizes that if H_2O molecules in atmosphere are a factor, which induce additional current flowing in the insulator material (Kapton/Aluminum thin film.), these different results are explained.

Classical Resistivity Method

In this experiment, a vacuum system was used, pictured 1 below.
Inside of the vacuum system, there is a capacitor, which is constructed from cupper, schematic diagram 1. The insulator material (Kapton/Aluminum thin film.) was placed between these capacitor plates, and constant voltages applied to the bottom plate from BARTAN 1.5 kV Power Supply. The upper plate is connected to KEITHELEY Picoammeter to measure the current flowing in this capacitor. This apparatus has a current resolution of 2 pA.
The insulator material (Kapton/Aluminum thin film) has polymer structure, and when it is placed in electric field, it polarizes such as schematic diagram 2.
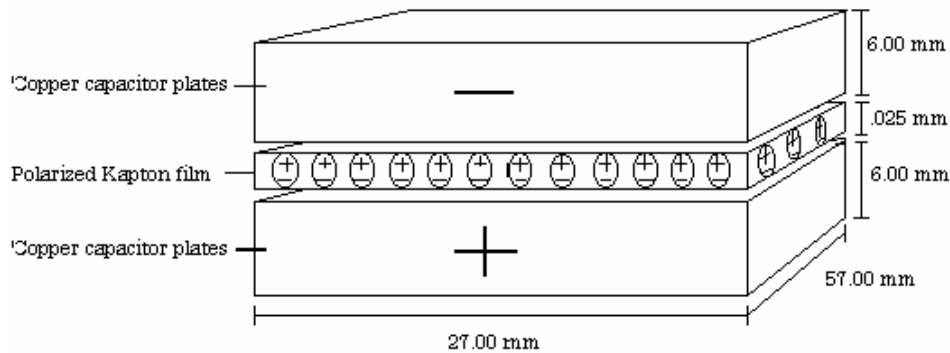
Figure 1   Vacuum system
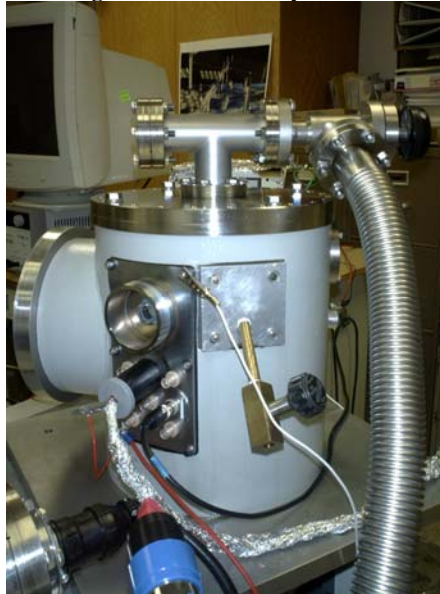
Schematic diagram 1   Inside of capacitor (cylindrical cupper in two small plates**)**
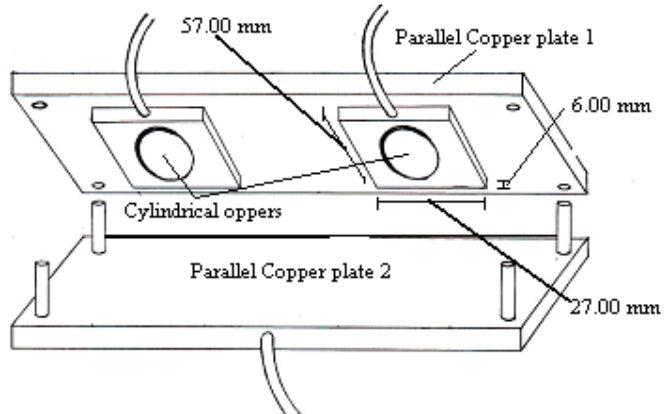
Schematic diagram 2   polarization of insulator material (Kapton/Aluminum thin film)

Experimental results

Graph 1 Current vs. Elapsed Time at Three different Constant Voltages. Each data set is 25 minutes long and 30 seconds of time interval.
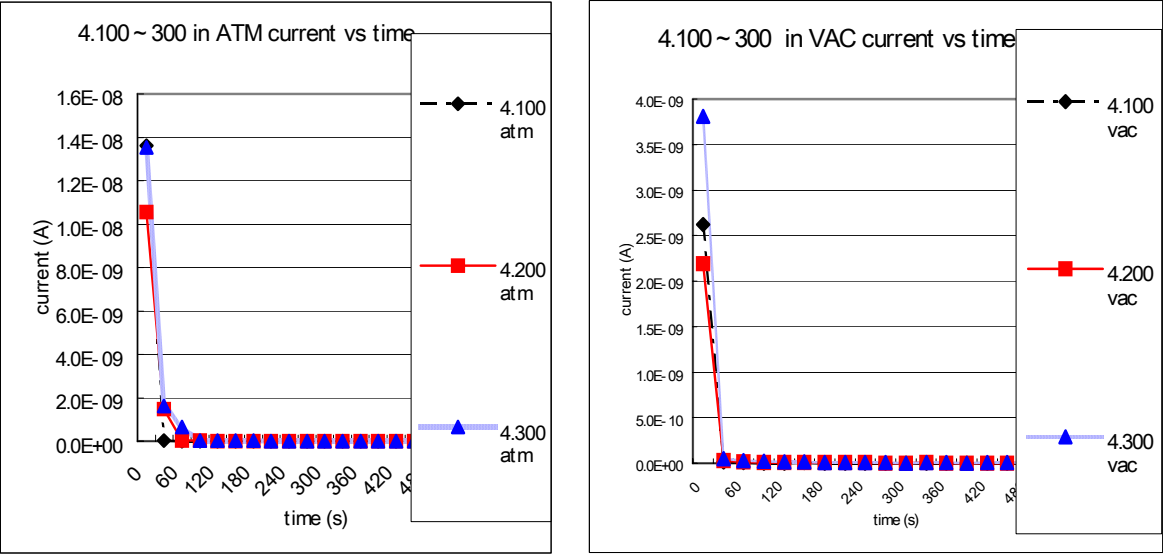
These are graphs for current vs. elapsed time at three different constant voltages in atmosphere on the left graph and vacuum on the right graph. These are typical f 150 such data sets. These data graphs can be modeled as an exponential decay of the following form,

$$I(t) = I_o \cdot e^{-\left(\frac{t}{\tau}\right)} \qquad \textcircled{1}$$

I_o is initial current, t is elapsed time, and τ is decay constant.

This is not unexpected for a capacitor this is charging.

Graph 2 A closer look of the graph 1: Effect of applied voltage.
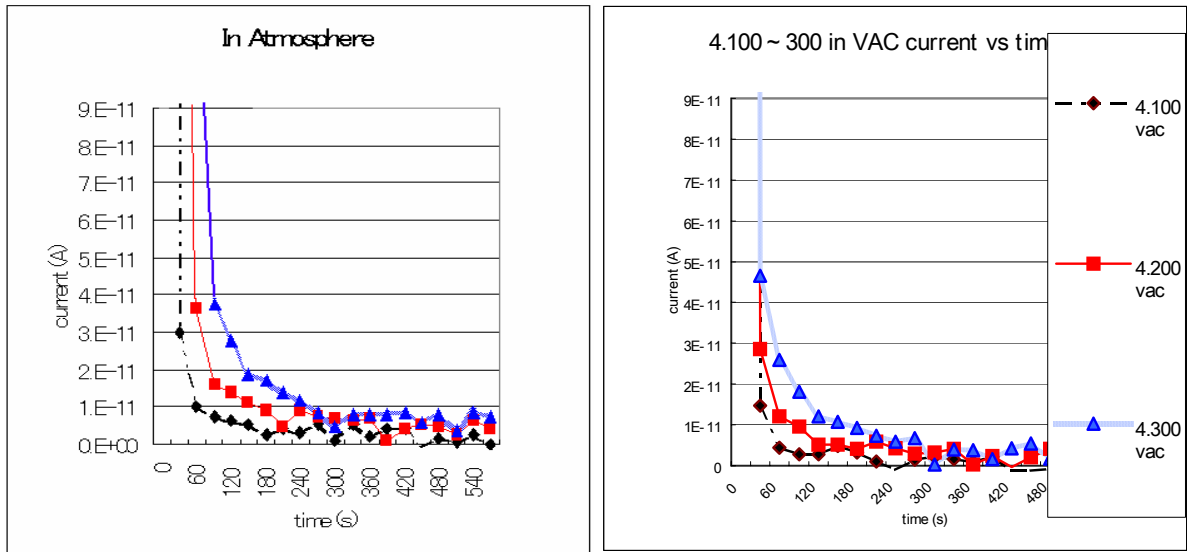
These data sets all have an asymptotic limit of ~2 pA, and this limit value corresponds to a resistivity (6.28±0.05) x 10^13 Ω-cm. Therefore, the measurable true resistivity with this method is 9.79 x 10 ^13 Ω-cm. (Note: this is effective upper limit of resistivity, based on the noise limit for current measurement of ~2 pA. Jerilyn Brunson has improved the instrument which now has a noise limit of ~0.1 pA.)

This explains why the Classical Resistivity Method is inaccurate for high resistivity insulators.

Table 1 Resistivity and Tau fits from simple model with three different constant voltages in atmosphere and vacuum

In Atmosphere					
	100 (V)		200 (V)		300 (V)
Resistivity (Ω-cm)	$6.228 \cdot 10^{13}$		$6.724 \cdot 10^{13}$		$7.219 \cdot 10^{13}$
Tau (s)	19.084 s		20.603 s		22.119 s
In Vacuum					
	100 (V)		200 (V)		300 (V)
Resistivity (Ω-cm)	$6.276 \cdot 10^{13}$		$6.276 \cdot 10^{13}$		$6.323 \cdot 10^{13}$
Tau (s)	19.229 s		19.23 s		19.374 s

Here are the numerical results from fits based on this simple model. From the measurement of amount of decay current flowing with time, and the size determination of the material and capacitor, we found the tau and resistivity.

Table 2   Initial current flowing and initial voltage in Atmosphere and Vacuum

Time	In Atmosphere							
	Current	Set 100 V		Current	Set 200 V		Current	Set 300 V
0 second	2.23E-08	18.493		1.15E-08	129.27		1.37E-08	277.8
30 second	3.20E-11	99.9		6.77E-10	200		2.79E-09	299.9
V gap between Atm and Vac	57.308 v			56.9 v			0.8 v	
Time	In Vacuum							
	Current	Set 100 V		Current	Set 200 V		Current	Set 300 V
0 second	1.03E-09	75.801		2.21E-09	186.17		3.59E-09	278.6
30 second	1.11E-11	99.9		3.22E-11	187.8		4.93E-11	300

The table 2 above shows initial voltages gaps between atmosphere and vacuum. For example, in the set 100 v in atmosphere and vacuum, their initial voltage gap is 57.308 volts.
(Note: We need keep it mind that BARTAN Power Supply always takes a little time to reach a set voltage value from 0 voltages.)

Compared the data result in atmosphere to vacuum

From the graph 1 above, it is easy to see the different amount of initial current flowing in atmosphere and vacuum data. For example, in atmosphere, the initial current is $1.4 \cdot 10^{-8}$ with 300 V, but in vacuum, the initial current is $3.6 \cdot 10^{-9}$ with 300 V. Therefore the initial current is one order of magnitude higher in atmosphere than in vacuum.

From the graph 2, the polarization decay time range over~1 to 2 minutes. In atmosphere the decay is more rapid for smaller applied voltages. Another way to say this is that tau is larger for smaller applied electric fields. In vacuum the effect of electric field is similar, but less pronounced and more complicated.

From the table 1, the resistivity for vacuum tests is very consistent. In the meantime, the resistivity for atmospheric measurements are very similar, but increase slightly with applied voltage.

From the table 2, those voltage gaps imply that Speed for reaching a set voltage from 0 voltage is different in atmosphere and vacuum. In other word, their relation is (in atmosphere) dV/dt > (in vacuum) dV/dt. For example, in the set 100v in atmosphere, the initial voltage is 18.493 v, but in vacuum, it is 75.801 v. This means that the dV/dt in atmosphere is slower. So it can be said that something resists this capacitor to reach the set 100 v in atmosphere.

As another notable point, the voltage gaps in atmosphere and vacuum decrease from 57.308 to 0.8 volts with increasing the set voltage from (Set 100 v) to (Set 300 v).

Analysis and Hypothesis

These differences must be caused with some factors in atmosphere because all this experiment has been done identically except this experiment in the different environments.

It can be assumed that several gases and liquid, which exist in the atmosphere, cause this difference. Moreover, it is thought that the H_2O molecules are especially effective factor for causing these differences. Because H_2O is great conductor and usually occupies 17.3 g per m³ at 193 K in atmosphere at ground level, this fact is thought to be enough reason for focusing on the H_2O molecules here.

As a hypothesis, H_2O molecules can have a potential to cause two remarkable behaviors in Kapton/Aluminum insulator material as follow:

1. Some H_2O molecules independently exist in the Kapton/Aluminum insulators that become great conductors without interaction of the polarizing the insulator.
2. Some H_2O molecules bound to Kapton/Aluminum polymers that disturb to polarize the Kapton/Aluminum polymer in an electric field.

These states will express; the initial current flowing are different in atmosphere and vacuum; the decay speed is faster for smaller applied electric field in atmosphere; resistivity increase slightly with applied voltage; there are the initial voltage gaps in atmosphere and vacuum; the initial voltage gap is larger for smaller applied electric field in atmosphere.

Theory

In the atmosphere, there are H_2O molecules inside of the Kapton/Alum insulator before applied voltage because H_2O molecules are small enough to leak into the Kapton/Alum polymer structures.

Theory for hypothesis 1, Some H_2O molecules independently exist in the Kapton/Alum insulator. They run additional current flowing into the Kapton/Alum insulator with ionization ($H_2O \rightarrow H^+ + OH^-$) in the Kapton/Alum insulator. It assumes that there is no interaction to the environment around them because once again states of them are independent each other and from Kapton Alum polymers. Furthermore, their speed for the ionizing is accelerated with increasing electric field. Therefore, it is possible to run one digit more of additional electric current flowing in the Kapton/Alum insulator in atmosphere than in vacuum where includes little H_2O.

Theory for hypothesis 2, Some H_2O molecules bound to Kapton/Aluminum polymers that disturb to polarize the Kapton/Aluminum polymer in an electric field.

Figure 1 This is an image schematic of that a H2O molecule bond to Kapton/Alum polymer with Van Der Waals bonding
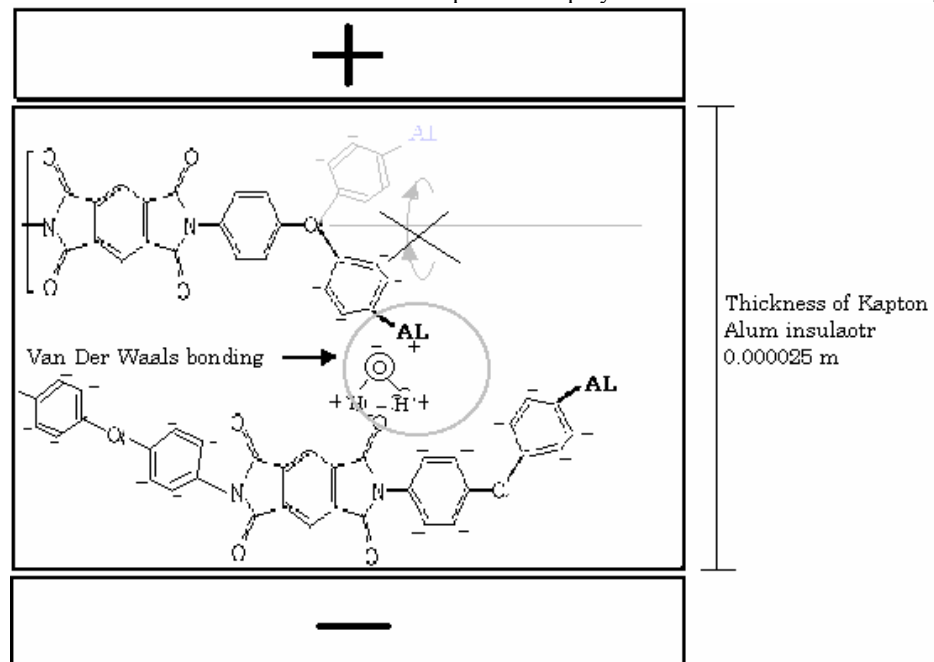
Some H_2O molecules bond to Kapton/Alum polymer before the voltage applied to them like a Figure 1 above. This is one of the examples when the voltage is applied to the Kapton/Alum insulator, the Van Der Waals bonding between H_2O and Kapton/Alum polymer disturb the dipole of Kapton/Alum polymer to spin and array along the electric field. Although the bondings gradually break up with increasing the electric field, at first they resist increase the electric field by BERTAN power supply. Therefore, in atmosphere, the speed for reaching a set voltage is slower than in vacuum. However, in atmosphere, as the high voltage set such as set 300 v is applied to the capacitor, the bonding is broken quicker than the low voltage like set 100 v. Therefore, the voltage gaps between in the atmosphere and vacuum are smaller as the applied set voltage is increase.

Confirmation of the Theories

From the theory above, different decay speeds in atmosphere are also explained. The additional current flowing in the Kapton/Alum insulator can change decay speed by following

From the equation ①

$$I(t) = I_0 \cdot e^{-\left(\frac{t}{\tau}\right)}$$

when the tau is large, the curve is graph 2 becomes gentler (decay speed slower with higher voltage.) The tau consist of resistance R and capacitance C_0 such that

$$\tau \text{ (tau)} = R_{total} \cdot C_0 \qquad ②$$

the capacitance C_0 increases with increasing permitivity between the capacitor plates. (Note: In this case, the permitivity correspond to a permitivity of the sample insulator material (Kapton/Aluminum thin film.))

$$C_0 = \varepsilon \cdot S / d$$

where ε is dielectric constant of the sample insulator material, S is area of the capacitor plate, and d is distance between capacitor plates.

$$\varepsilon = \varepsilon_r \cdot \varepsilon_0$$

ε_0 is dielectric constant in vacuum, and ε_r is relative permitivity. (Note: water of relative permitivity is about 80, which is very large.)

This means that Kapton/Alum insulator has very small relative permitivity. However, if there is some H_2O in the insulator, the entire relative permitivity of the insulator increase because H_2O has very large relative permitivity. Furthermore, the more H_2O molecules corporate to rise up the relative permittivity as the higher constant voltage applied, such as schematic diagram 3 below.

Diagram 3 Mechanics of Dielectric constant and permitivity in different electric fields
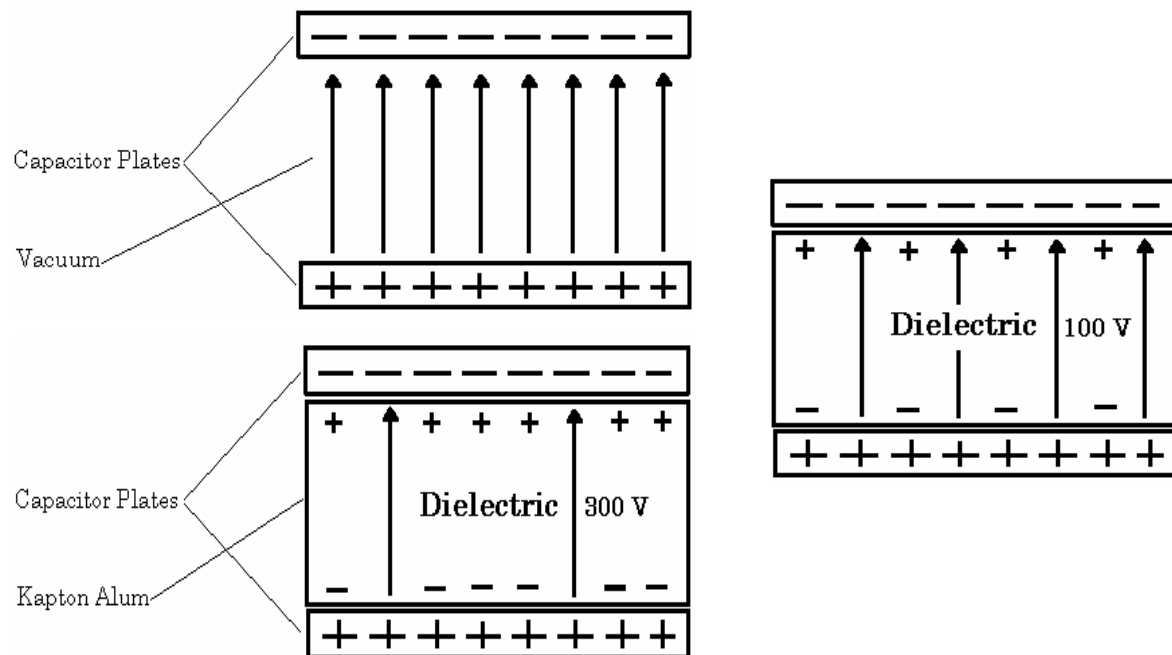
This corresponds to the greater dielectric constant of the insulator ε than low set voltage applied. What the dielectric constant gets larger means the capacitance C_0 is greater. As a result, equation ① has larger tau with higher set voltage from the equation ②. This is why the decay speed is faster within small electric field.

This theory is defended by the frequency dependence of the polarization or dielectric constant, below,
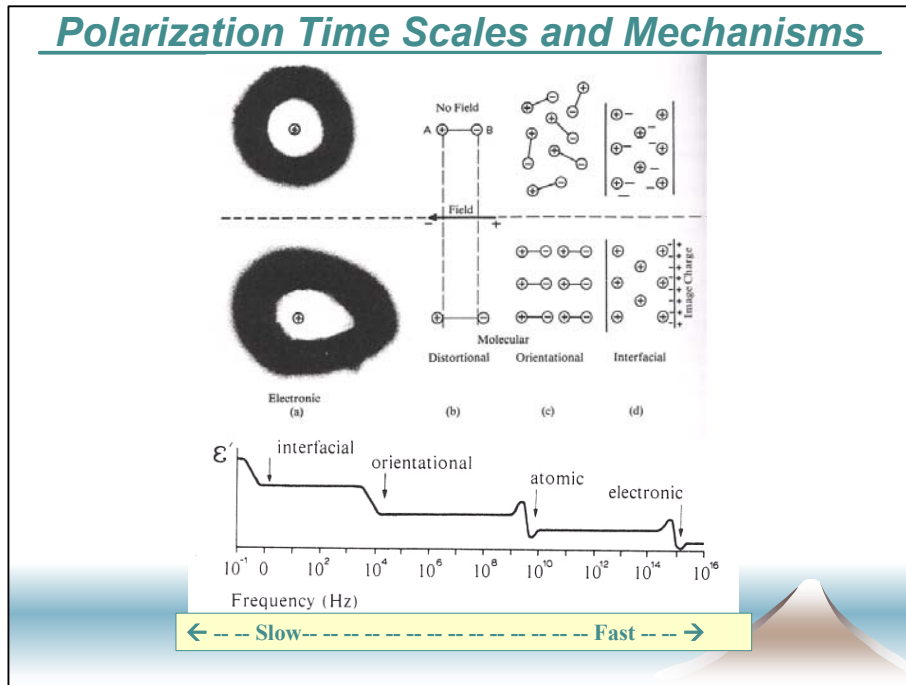
Figure.   The frequency dependence of the polarization or dielectric constant. (bottom)   The dielectric constant decreases with increasing frequency of the applied electric field, as the response of the polarization mechanisms are unable to keep up with the more rapidly changing electric field.   Response times for typical materials are indicated in the graph.   (top)   Schematics of polarization mechanisms in order of decreasing response time, there are (a) distortions of the electron probability density around atoms, (b) distortion of the molecular charge density, (c) reorientation of dipolar moleculesto align opposite to the E-field, and (d) migration of charge to the material interfaces.

This Figure is quoted from J.R.Dennison, "NASA Space Environments and Effects Program," Resistivity Measurements Related to Spacecraft Charging **Draft,** Logan, UT, April, 1, 2002 to January 31, 2005.

Conclusions

1. The true resistivity of Kapton thin film insulators cannot be accurately measured with the Classical Resistivity Method due to inherent instrumental limitations of two methods.
2. The presence of H_2O in atmospheric measurement strongly affects measurement made on seconds' time scales. Most accurate measurements need t be made in vacuum.
3. In atmosphere, both the initial current and the polarization rate very with applied electric field. These effects are affected to the response of dipolar molecule, radicals, or ions to the electric field.

References

[1]   Holbert, Spacecraft Charging,
http://www.eas.asu.edu/~holbert/eee460/spc-chrg.html, September 22, 2003.

[2]   E.I.   du Poin de Nemours and company
http://www.dupont.com/kapton/index.html

[3] Kapton polyamide film product information: PHYSICAL PROPERTIES, REPORT
H-38492-1,   (Dupont,   Wilmington,   DE,   February,   1997);
http://www.dupontteijinfilms.com/

[4]   C.D Thomason, V. Zavyalow, J.R. Dennison, Jodie Corbridge, "Electron
Emission Properties of Insulator Materials Pertinent to The International Space Station,"
Proceedings of the 8th Spacecraft Charging Technology Conference, October 20-24,
2003, Huntsville, Alabama.

[5]   J.R. Dennison, Prasanna Swaminathan, A.R.Frederickson, Alec Sim, Jerilyn
Brunson, and Eric Crapo, "COMPARISON OF CLASSICAL AND CHARGE
STORAGE METHODS FOR Technology Conference, October 20-24, 2003, Huntsville,
Alabama. DETERMINING CONDUCTIVITY OF THIN FILM INSULATORS", 8th
Spacecraft Charging

[6]   J.R. Dennison, A.R. Frederickwon, Prasanna Swaminathan, "CHARGE
STORAGE, CONDUCTIVITY AND CHARGE PROFILES OF INSULATORS AS
RELATED TO SPACCRAFT CHARGING", 8TH Spacecraft Charging Technology
Conference, October 20-24, 2003, Huntsville, Alabama.

[7]   Mueller. Ahlhorn, "Kapton [®]" http://www.mueller-ahlhorn.com

[8]   Aaron Snyder and Kim K. de Groh, "THE DEPENDENCE OF ATOMIC
OXYGEN UNDERCUTTING POLYIMIDE KAPTON[®] H UPON DEFECT SIZE",
Fifth International Conference on Protection of Materials and Structures of LEO Space
Environment, June 2001,Glenn Research Center, Cleveland, Ohio.

[9] J.R.Dennison, "NASA Space Environments and Effects Program," Resistivity
Measurements Related to Spacecraft Charging **Draft,** Logan, UT, April, 1, 2002

to January 31, 2005.