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Resistivity of Kapton E at Intermediate Time Scales Following High-Energy Electron Irradiation

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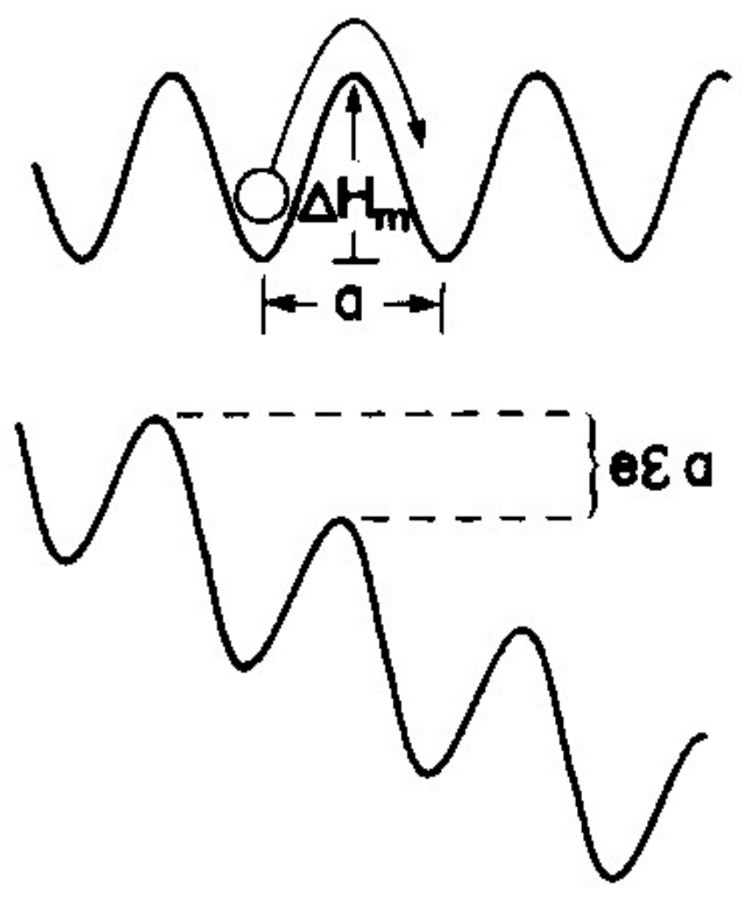
Hopping Conductivity

Theoretical models of conductivity of highly insulating materials, such as Kapton E, are most often based on hopping conductivity models. These models were originally developed, and since verified for disordered semiconductors However, the validity of these models for polymers is unclear.



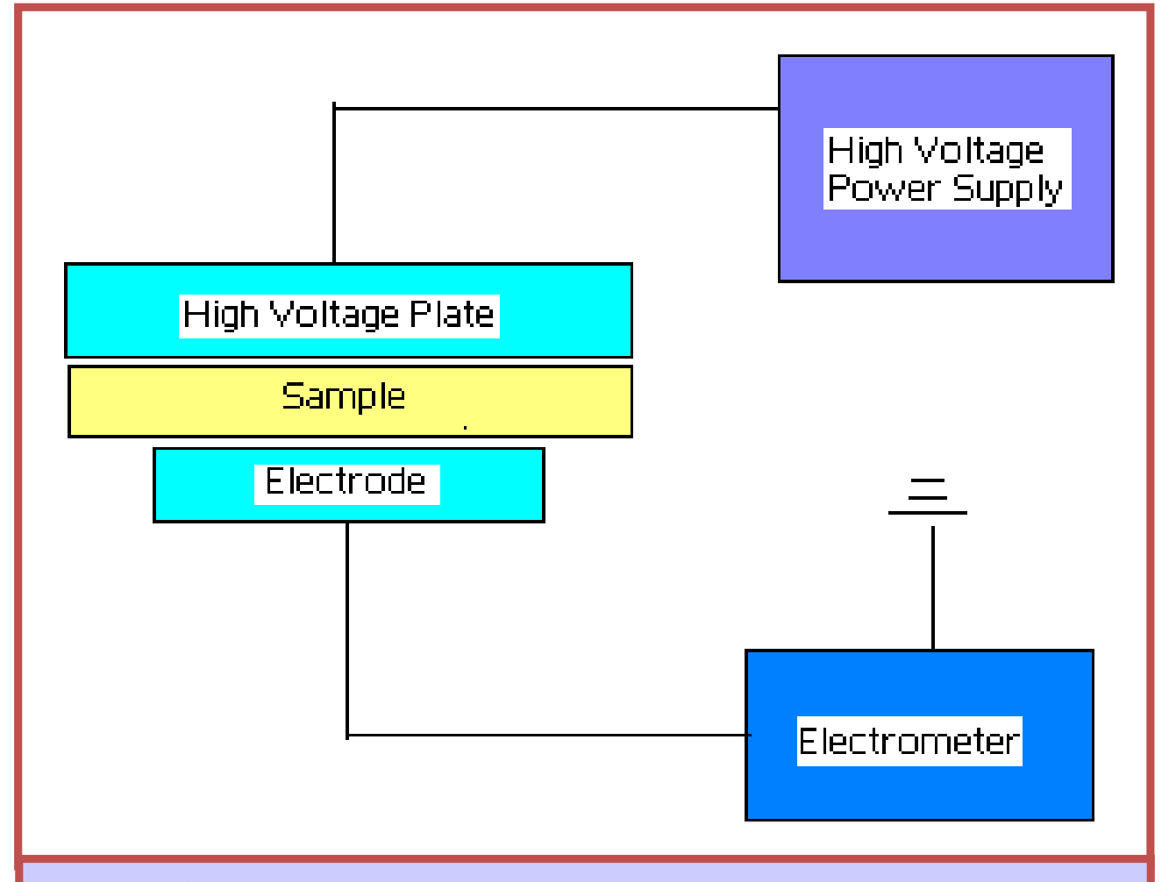
The theory of thermal assisted hopping conductivity, developed by Mott and Davis, provides a model for the temperature and electric field dependence of the dark current conductivity of materials.

$$\sigma_{hop}(E,T) = \left[\frac{2\cdot n(T)\cdot \nu\cdot a \quad \cdot e}{E}\right]\exp\left[\frac{-\Delta H}{k_B\cdot T}\right]\sinh\left[\frac{\varepsilon\cdot E\cdot a}{2\cdot k_B\cdot T}\right]$$

Charge carriers are trapped in a localized potential well of depth *ΔH* and uniform separation *a*. Quantum mechanical tunneling between localized states is driven by thermal hopping. An applied electric field causes charge migration to be favored in the field direction.

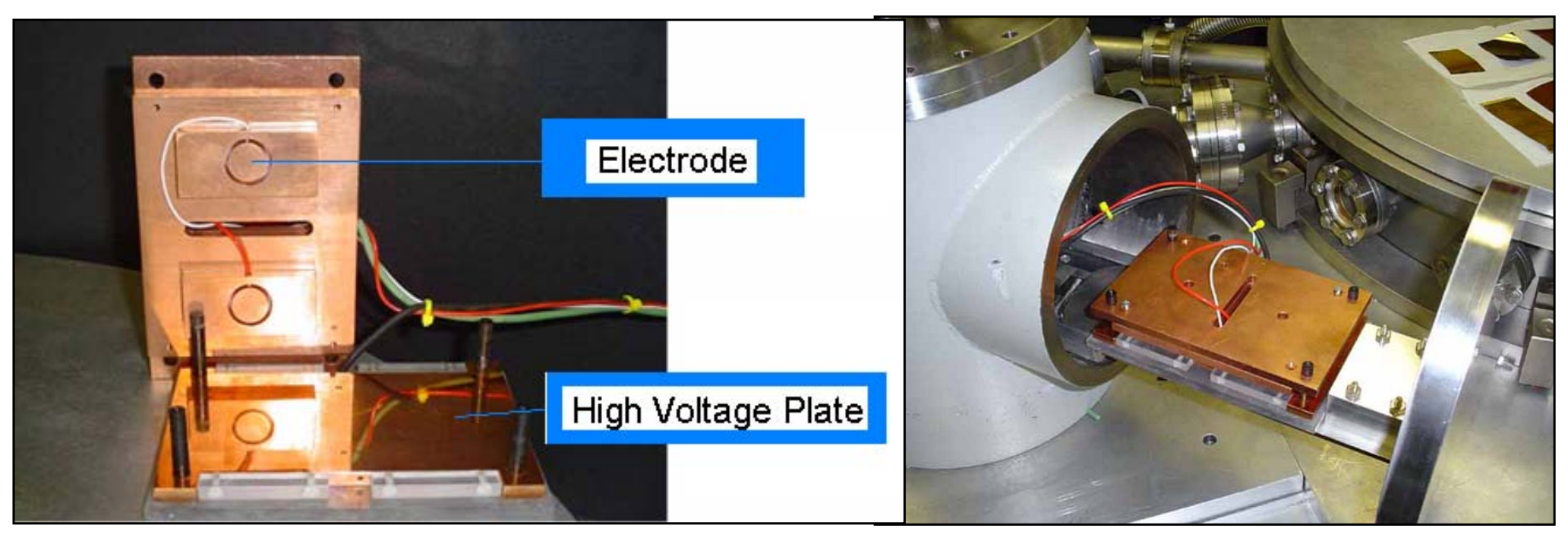
Measuring Resistivity

Constant Voltage Method



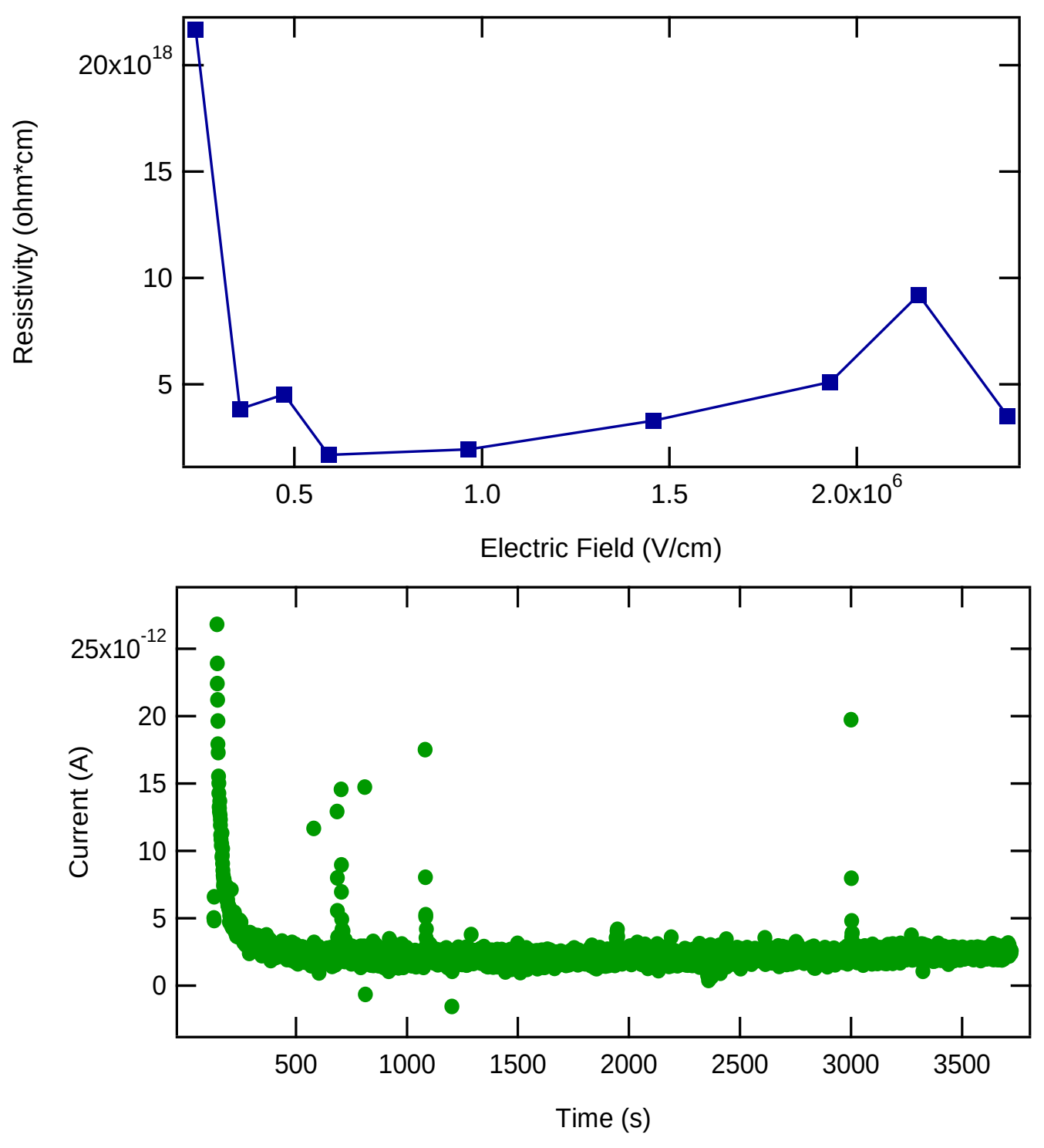
Simplified Schematic of the constant voltage method. A thin polymeric sample, sandwiched between two plates is subject to an electric potential, driving current through the sample. A high resolution electrometer measures the current, and thus resistivity may be calculated.

The Apparatus



Our Constant Voltage Apparatus is capable of measuring currents in the femto-amp range. This allows materials with unusually high resistivities to be measured. Samples are carefully cleaned, mounted, and vacuum-baked before placement in the chamber. (Base pressure < 10^{-4} Torr.

Unexposed Kapton E Resistivity



The top graph is an example of a data set for determining the resistivity. The current approaches an asymptotic limit, and it is this current which is used to calculate the material's resistivity. The resistivity is somewhat dependent on electric field magnitude (shown in graph above to the right), but the effect is relatively small, typically less than an order of magnitude. The average resistivity of Kapton E has been determined at 3 x 10^{18} ohm·cm.

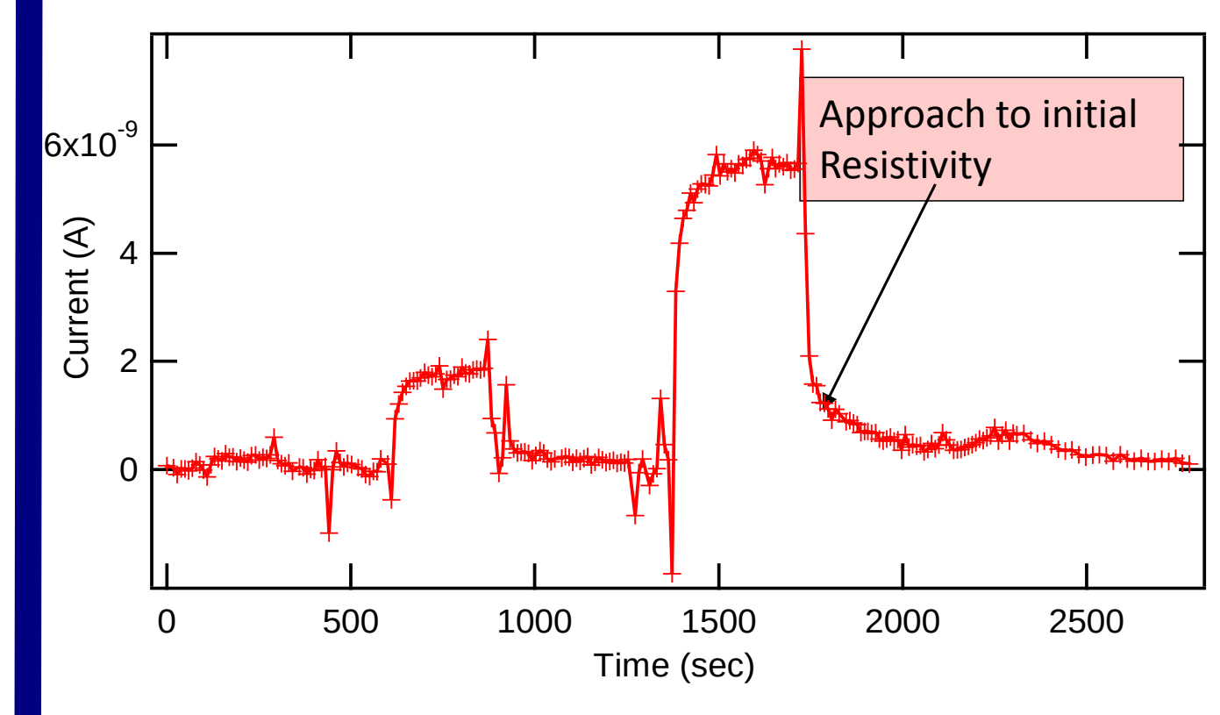
Kapton E is a polyimide film with several interesting characteristics, including a high resistivity and a low out-gassing rate, making it valuable in spacecraft and vacuum applications.

Main Findings

What We Measured

(Below) Current vs. elapsed time for a Kapton E sample subject to radiation dosage. Note a RIC current persists for ~ 10^3 seconds after the radiation ceases.

Total Dosage: 5.5 kRads



Resistivity of an irradiated Kapton E sample was tested 16 days after radiation exposure, to look for long term effects. No electric field had been applied to this sample during irradiation. Using the constant voltage method, we determined the resistivity at several electric field strengths (table at right). The average measured resistivity was a full *order of magnitude less* than that exhibited by unexposed Kapton E.

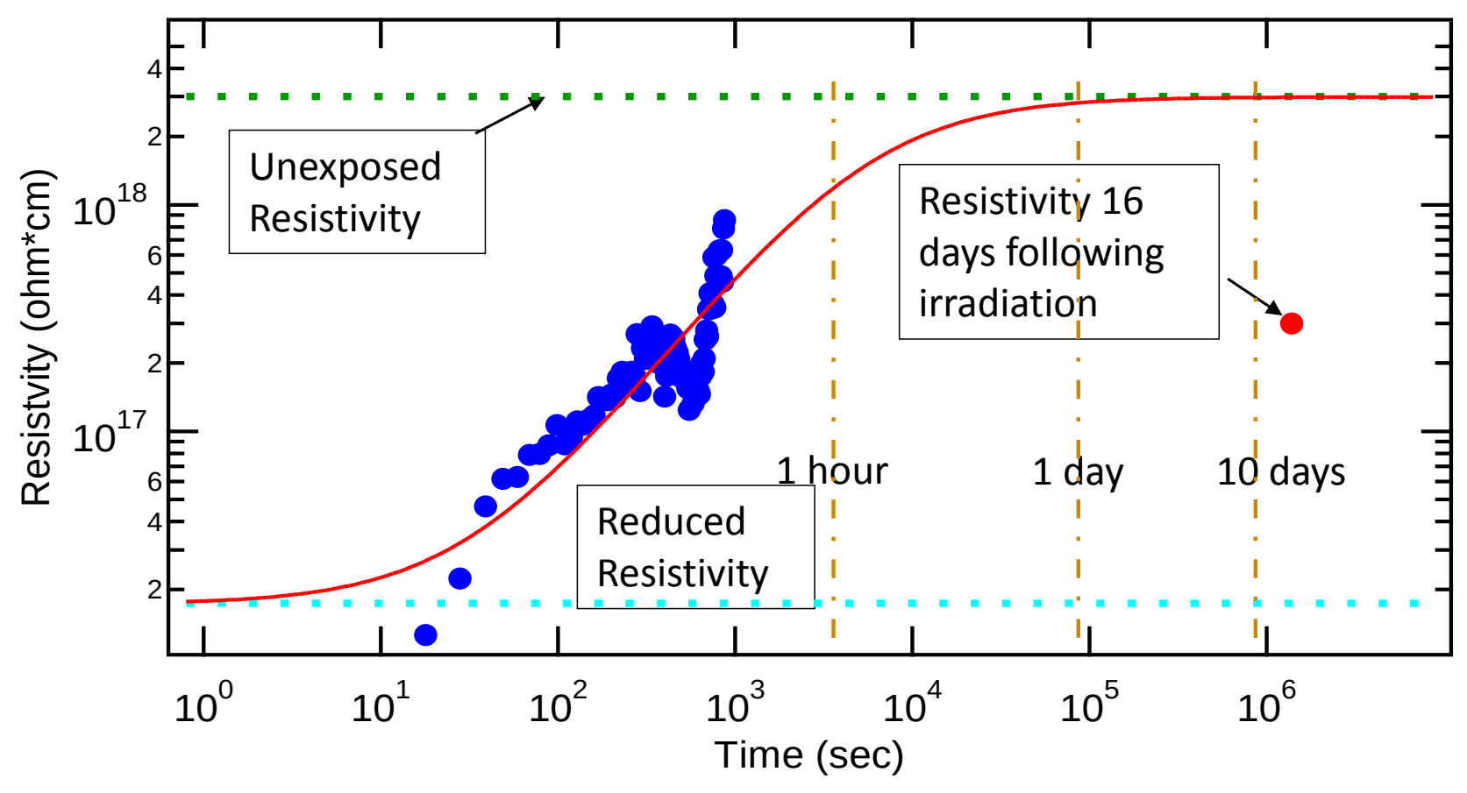
Applied Voltage	Calculated Resistivity
1500 V	1.99 (±0.05) x 10^{17} Ω-cm
2100 V	2.66 (±0.05) x 10^{17} Ω-cm
2450 V	3.17 (±0.05) x 10^{17} Ω-cm
3000 V	3.97 (±0.05) x 10^{17} Ω-cm
3600 V	3.16 (±0.05) x 10^{17} Ω-cm
4200 V	2.20 (±0.05) x 10^{17} Ω-cm
4800 V	5.26 (±0.05) x 10^{17} Ω-cm

What We Might Have Expected

The equation below models the time-dependent contribution of the persistent RIC to the total resistivity of the sample. When a pulse of radiation ceases, the current decays from an enhanced level to the dark current level. Equivalently, the resistivity rises from a lower, radiation induced level to its dark current level. This is shown by the red line in the figure to the right.

$$\frac{1}{\rho_{.total}(t)} = \frac{1}{\rho_{.RICinitial}\left(1+\frac{b\cdot t}{T}\right)} + \frac{1}{r_{.DC}}$$

Equation Parameters:
p_{total}: Total value of resistivity
$P_{RICinitial}$: Initial value of RIC resistivity (from when irradiation ceases)
b: Fitting parameter
t: Time
T: Temperature
p_{DC}: Dark current resistivity value



(Above) Data (blue) are fit by the total resistivity equation (red line). These data are show the resistivity of a Kapton E sample, immediately following the cessation of the final radiation pulse. This sample received the same dosage of irradiation as the Kapton E sample which we measured using the constant voltage method (Table above). The constant voltage data (red dot) is approximately a full order of magnitude lower than expected. After ~ 1 day, we would have expected to find the resistivity at nearly its DC level. The large discrepancy is most surprising.

Possible Causes for Discrepancy

We consider three probable causes for the discrepancy between the measured and predicted post-exposure resistivity

- **The Kapton E sample received permanent damage**

Although the dosage threshold for permanent damage is conventionally much greater (~1 Mrad) than what we used, this explanation is inviting. While performing constant voltage tests, the sample experienced electrostatic breakdown at 4800 V, just 69% of the manufacturer's value for breakdown. To further examine this possibility we have in our possession three Kapton E samples that have been irradiated with dosages ranging from 2.4 Mrads to 2500 Mrads. We hope to soon report on testing results of these samples.

- **It is the result of experimental details, not yet fully considered**

As explained above, the data to which we fit the resistivity model and the data which we tested 16 days later came from different samples of Kapton E. The constant voltage tested sample was not subject to an applied electric field during the time of the irradiation. Both samples were near liquid nitrogen temperatures while irradiated. The full effects of these and other details cannot be adequately understood without more data.

- **Our constant voltage measurement is anomalous**

Certainly we cannot hope to justify such a large discrepancy based on what amounts to a single data point. If such a discrepancy is justified, we will need more data to reasonably prove so.

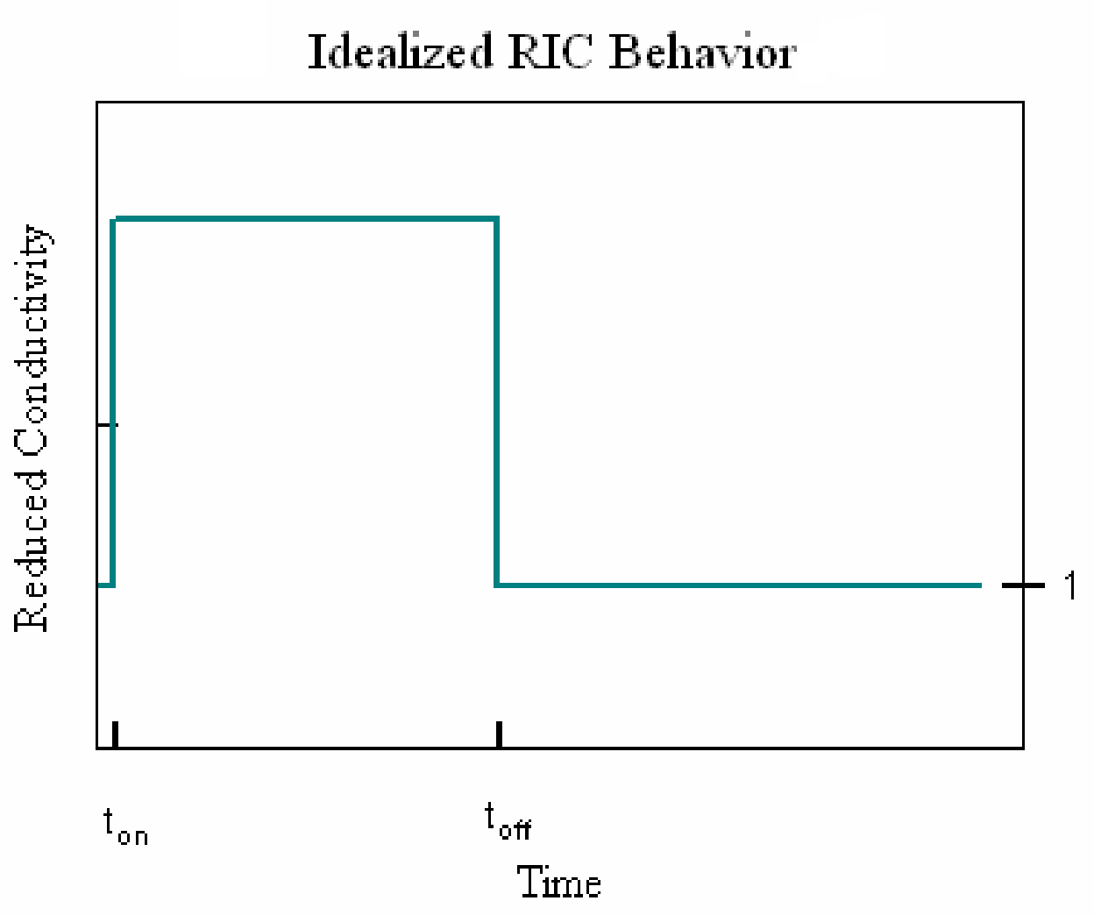
Summary & Conclusions

- **A highly-insulating polymer, Kapton E, was subjected to high-energy irradiation, receiving a dosage of about 5.5 kRads.**
- **Theoretical modeling of the persistent RIC resistivity after irradiation predicts a rise to the unexposed level of resistivity after a finite amount of time.**
- **Based on data obtained from another sample that received an identical dosage, we would predict that after approximately 1 day the measured resistivity would be at the unexposed level.**
- **We measured our sample 16 days after irradiation, and found its resistivity a full order of magnitude less than expected.**
- **Possibilities for discrepancy include permanent sample damage, experimental details not fully considered, or anomalous measurement.**
- **Substantially more data are needed to fully understand the problem. Plans include measuring the resistivity of Kapton E samples that received more considerable radiation dosages.**

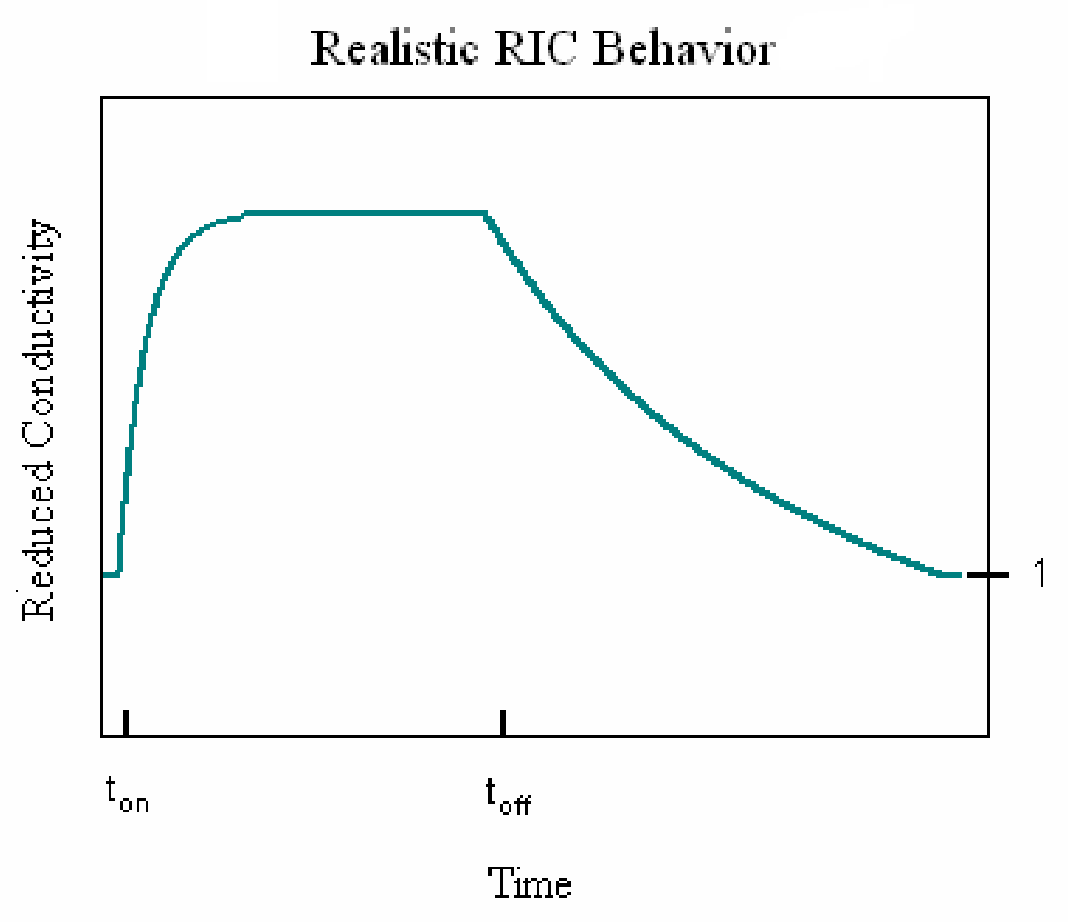
Radiation Induced Conductivity

Theoretical Background

As materials are bombarded with high energy radiation, absorbed energy is shared with many valence electrons The conductivity is enhanced by $\sigma_{ric} = kD^{\Delta}$, where D is the dosage rate, Δ is typically one, and k is a material dependent proportionality constant.



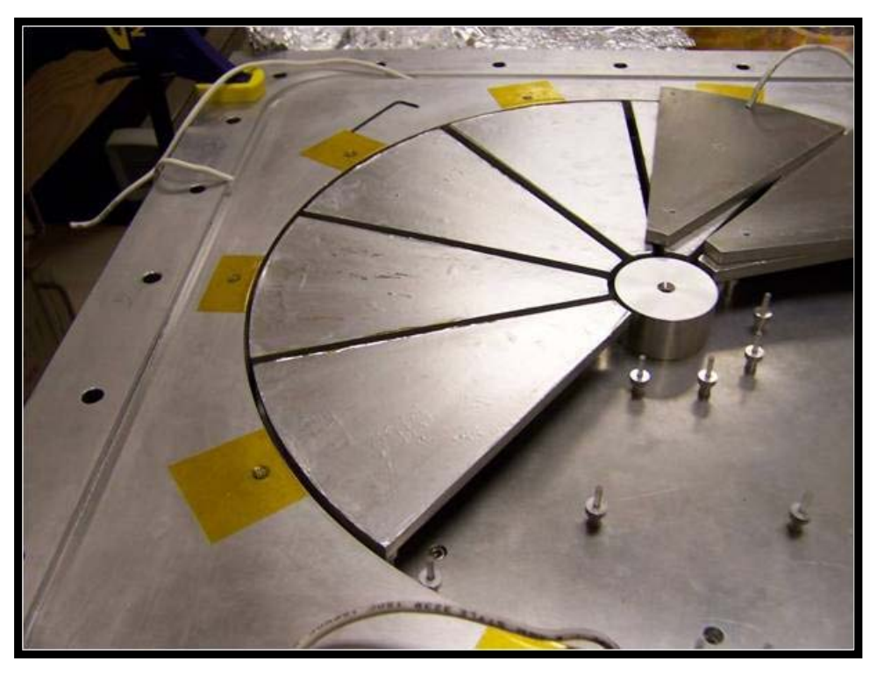
In an idealized model, when incident radiation begins at t_{on}, the conductivity is enhanced instantaneously. Once the radiation ceases, the enhancement disappears instantaneously.



In reality, when the radiation is turned on, a finite time is required for the measured conductivity to attain the radiation induced level.

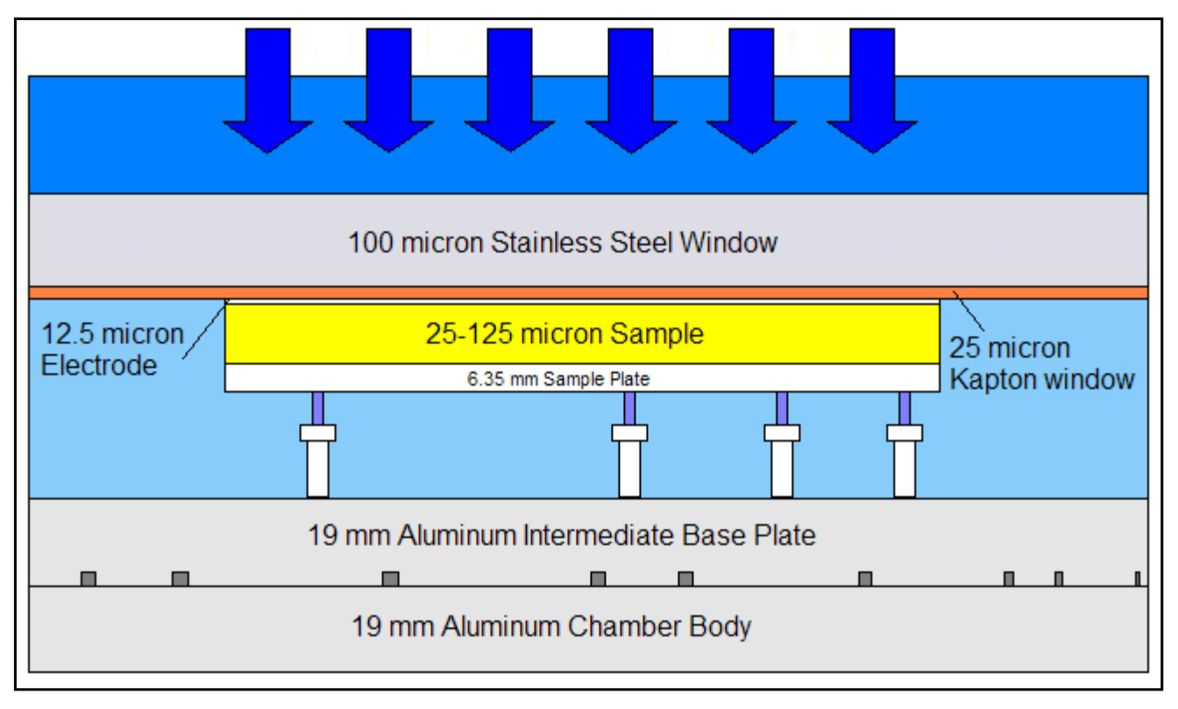
Similarly, when the radiation ceases, the measured conductivity again takes a finite amount of time to decay to the initial level due to persistent RIC effects

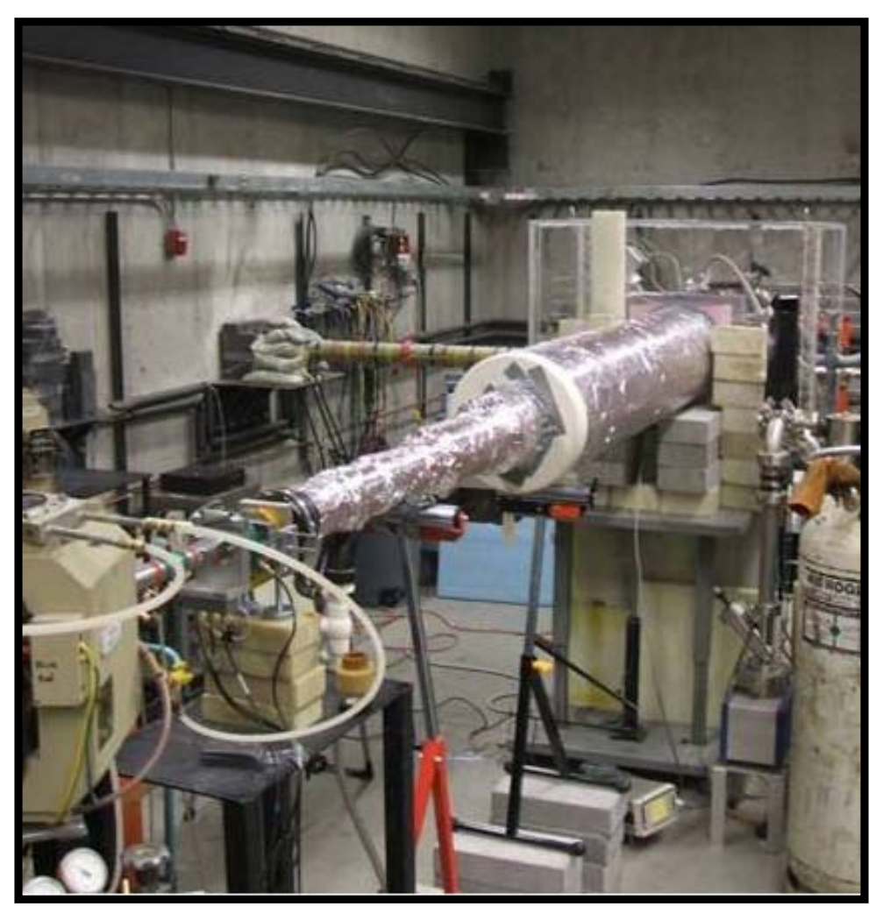
The Apparatus and Measurements



The apparatus used to make RIC measurements included the vacuum chamber, interior of which is shown to the left. Using a combination of a picoammeter and a multiplexer, data could be taken simultaneously on 10 different large area, thin polymer samples.

A major design hurdle consisted of having as little mass between the sample and incoming radiation, while holding vacuum in the chamber. The diagram to the right (not to scale) shows how this was accomplished.





The figure to the left shows our assembly at the Idaho Accelerator Center. We employed a 25 MeV LINAC accelerator to bombard our samples with high-energy electrons at 4 MeV at a dose rate of 0.01 to 10 Rad/s.

Spacecraft Charging

Solar panel damaged by localized charging event

Interaction with the plasma environment induces spacecraft charging. Electron, ion, and photon charge-induced potentials can result in arcing, thus damaging electronics, solar panels (at left), or other spacecraft components. Understanding how charge migration and dissipation occurs in insulators is crucial to mitigating the effects of spacecraft charging.

~1/3 of all spacecraft failures and anomalies due to the space environment result from plasma-induced charging

Spacecraft charging can be driven by the electron emission properties of materials from lower incident energy particles interacting near the surface. Such surface charging can lead to damage such as the arcing of the solar array shown above.

Alternately, deep dielectric charging of insulators within the spacecraft by higher incident energy particles can result in internal electrostatic discharge like that shown at right.