Time-Evolved Constant Voltage Conductivity Measurements of Common Spaceborne Polymeric Materials

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Time-Evolved Constant Voltage Conductivity Measurements of Common Spaceborne Polymeric Materials

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- Transport Mechanisms in HDIM and Conductivity Model
- Measurement Limits and Critical Times
- Experimental Setup and Sample Preparation
- Results and Comparison

Bulk Conductivity NOT a Constant
Charge Transport in HDIM

- High Disorder Leads to Localized Defect Trap States Within Mobility Gap
- Power Law Distribution of Capture Times
- Dispersive Transport Behavior

Energy

Charge Injection

Diffusive

Dispersive

Dispersive Transport

\[ \sigma_{disp} t^{-(1-\alpha)} \]
Pre-Transit Time

\[ \sigma_{trans} t^{-(1+\alpha)} \]
Post-Transit Time

\( \alpha \) dispersion parameter describing the energy width of the Density of Trap States within the mobility gap

Transit Time for Semiconductors \( \sim 10^{-5} - 10^{-2} \) secs

Transit Time for HDIM \( \sim 10^4 - 10^6 \) secs
Macroscopic Charge Transport Mechanisms

\[ \sigma(t) = \sigma_{\text{DC}} + \sigma_{\text{pol}} e^{-\frac{t}{\tau_{\text{pol}}}} + [\sigma_{\text{disp}} t^{-(1-\alpha)} + \sigma_{\text{trans}} t^{-(1+\alpha)}] + \sigma_{\text{AC}} + \sigma_{\text{RIC}} \]

\[ \sigma(t) = \frac{J(t)}{F(t)} = \frac{I(t) \cdot d}{V \cdot A} \]

- \( \sigma_{\text{DC}} \equiv q_e n_e \mu_e \) **dark current or drift conduction**—very long time scale equilibrium conductivity.

- \( \sigma_{\text{pol}}(t) \equiv [(\varepsilon_r^\infty - \varepsilon_r^0) \varepsilon_o / \tau_{\text{pol}}] \cdot e^{-\frac{t}{\tau_{\text{pol}}}} \) long time exponentially decaying conduction due to **polarization**

- \( \sigma_{\text{dispsersive}}(t) \equiv \begin{cases} \sigma_{\text{disp}}^0 \cdot t^{-(1-\alpha)} & ; (\text{for } t < \tau_{\text{transit}}) \\ \sigma_{\text{transit}}(t) \equiv \sigma_{\text{trans}}^0 \cdot t^{(1+\alpha)} & ; (\text{for } t > \tau_{\text{transit}}) \end{cases} \) **broadening of spatial distribution** of space charge through coupling with energy distribution of trap states.

- \( \sigma_{\text{AC}}(\nu) \equiv \sum_i [(\varepsilon_r(\nu) - \varepsilon_r^0) \varepsilon_o \frac{1}{1+(\nu/\nu_i)^2}] \) **frequency-dependent AC conduction**—dielectric response to a periodic applied electric field

- \( \sigma_{\text{RIC}}(t, \dot{D}; \tau_{\text{RIC}}^1, \tau_{\text{RIC}}^2) \equiv \sigma_{\text{RIC}}^0(\dot{D}(t)) \left( 1 - e^{-\tau_{\text{RIC}}^1/(t-t_{\text{off}})} \right) \left( 1 + (t-t_{\text{off}})/\tau_{\text{RIC}}^2 \right)^{-1} \) **radiation induced conductivity** term resulting from energy deposition within the material.

Refer to (Wintle, 1983), (Dennison et al., 2009), and (Sim, 2012)
Limits of Measurement and Uncertainties

\[ \sigma(t) = \sigma_{DC} + \sigma_{pol} e^{-(t/\tau_{pol})} + [\sigma_{disp} t^{-(1-\alpha)} + \sigma_{trans} t^{-(1+\alpha)}] + \sigma_{AC} + \sigma_{RIC} \]

CVC

Noise Sources

- Thermal
- \( \sigma_{AC} \)
- \( \sigma_{RIC} \)
- Electrometer Noise

Estimated Contributions to Conductivity

- \( \Delta I_{J_N} \approx 4 \times 10^{-18} A \quad \rightarrow \quad \sigma \approx 6 \times 10^{-24} (\Omega \cdot cm)^{-1} \)
- Displacement current due to voltage ripple
  \[ \rightarrow \quad \Delta V \approx 0.02\% \quad (Battery) \]
- RIC from cosmic microwave background for LDPE
  \[ \rightarrow \quad \sigma \approx 4 \times 10^{-23} (\Omega \cdot cm)^{-1} \]
- \( \Delta I \approx 2 \times 10^{-15} A \quad \rightarrow \quad \sigma \approx 3 \times 10^{-21} (\Omega \cdot cm)^{-1} \)
Critical Time Scales and Conductivities

\[ \tau_{\text{decay}} = \frac{\varepsilon_0 \varepsilon_r}{\sigma} \]

Corresponding Resistivities \((\varepsilon_r = 1)\)

- 1 min \(\rightarrow \rho \varepsilon_0 \sim 1 \times 10^{-15} (\Omega \cdot cm)^{-1}\)
- 1 hr \(\rightarrow \rho \varepsilon_0 \sim 3 \times 10^{-17} (\Omega \cdot cm)^{-1}\)
- 1 day \(\rightarrow \rho \varepsilon_0 \sim 1 \times 10^{-18} (\Omega \cdot cm)^{-1}\)
- Limit \(\sim 1 \text{ yr} \rightarrow \rho \varepsilon_0 \sim 3 \times 10^{-21} (\Omega \cdot cm)^{-1}\)
- 15 yr \(\rightarrow \rho \varepsilon_0 \sim 2 \times 10^{-22} (\Omega \cdot cm)^{-1}\)
- 500 yr \(\rightarrow \rho \varepsilon_0 \sim 1 \times 10^{-24} (\Omega \cdot cm)^{-1}\)

\(\tau_Q < \tau_{\text{pol}} < \tau_{\text{transit}} < \tau_{\text{decay}} < \tau_{\text{eq}} < \tau_{\text{exp}}\)
Constant Voltage Conductivity

- Time evolution of conductivity
- $<10^{-1} \text{s to } >10^6 \text{s}$
- $\pm 2 \times 10^{-15} A$ resolution
- $\Delta I \approx 3 \times 10^{-16} A$
- $\sim 100 \text{ K} < T < 375 \text{ K}$

$$\sigma(t) = \frac{J(t)}{F(t)} = \frac{I(t) \cdot d}{V(t) \cdot A}$$

V(t) → V with Battery
LDPE Results

Removing DC from the data exposed the ‘Kink’

\[ \sigma(t) = \sigma_{DC} + \sigma_{pol} e^{-\left(\frac{t}{\tau_{pol}}\right)} + [\sigma_{disp} t^{-(1-\alpha)} + \sigma_{trans} t^{-(1+\alpha)}] \]

\[ \sigma_{DC} = 8.4 \pm 0.3 \times 10^{-19} (\Omega \cdot \text{cm})^{-1} \quad @ \quad 23.9^\circ\text{C} \]

\[ \sigma_{pol}^{0} = 9.0 \times 10^{-19} (\Omega \cdot \text{cm})^{-1} \]

\[ \tau_{pol} = 2.4 \text{ min} \]

Transit Time = 20.5 hours

\[ \alpha = 0.6 \]
Averages of conductivity taken near end at the same temperature over cycles

Equilibrium defined as when the transitive contribution falls below instrument error and when the total fit agrees with the dark conductivity
2 polarization contributions of greater magnitude but smaller time constant than LDPE

\[
\sigma_{pol}^0_1 = 1.0 \times 10^{-17} (\Omega \cdot cm)^{-1} \quad \tau_{pol}^1 = 0.1 \ min
\]

\[
\sigma_{pol}^0_2 = 1.8 \times 10^{-18} (\Omega \cdot cm)^{-1} \quad \tau_{pol}^2 = 0.5 \ min
\]

\[
\sigma_{pol}^0_1 = 9.0 \times 10^{-19} (\Omega \cdot cm)^{-1} \quad \tau_{pol} = 2.4 \ min
\]
PEEK Results

- Low dark conductivity --> Dispersive main contributor
- Polarization and DC similar to Kapton
- Transit and equilibrium time similar to LDPE of ~18 hours
Polypropylene Results

- LARGE Temperature Effects
- Dark Conductivity Right Near the Limit of Measurement \( \sigma_{DC} \approx 3 \times 10^{-18} (\Omega \cdot cm)^{-1} \)
- Very Long Equilibrium Time

15th SCTC Kobe, Japan 2018
Conclusions

- Bulk conductivity reduces in time, with most of the reduction happening within the first few hours of charge injection
- Reduction should be taken into account when modeling charging
- This along with conductivity enhancers should be considered in terms of decay time and specific flight and rotational characteristics
- Temperature control as next step for future measurements

Thank You