1-25-2018

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

Brian Wood
Utah State University

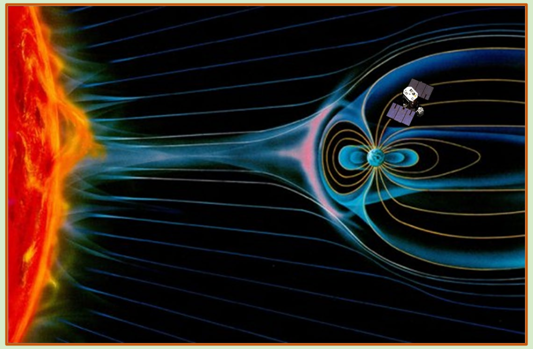
David King
Utah State University

JR Dennison
Utah State Univesity

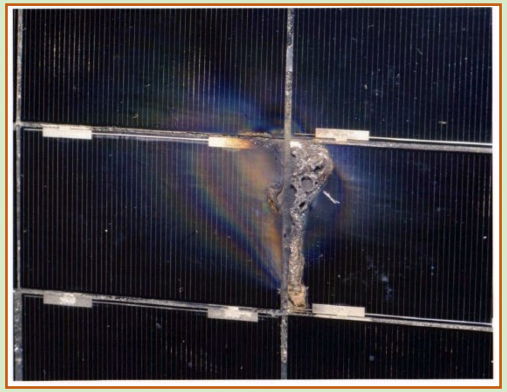
Time-Evolved Constant Voltage Conductivity Measurements of Common Spaceborne Polymeric Materials

Brian Wood, David King, JR Dennison
Utah State University

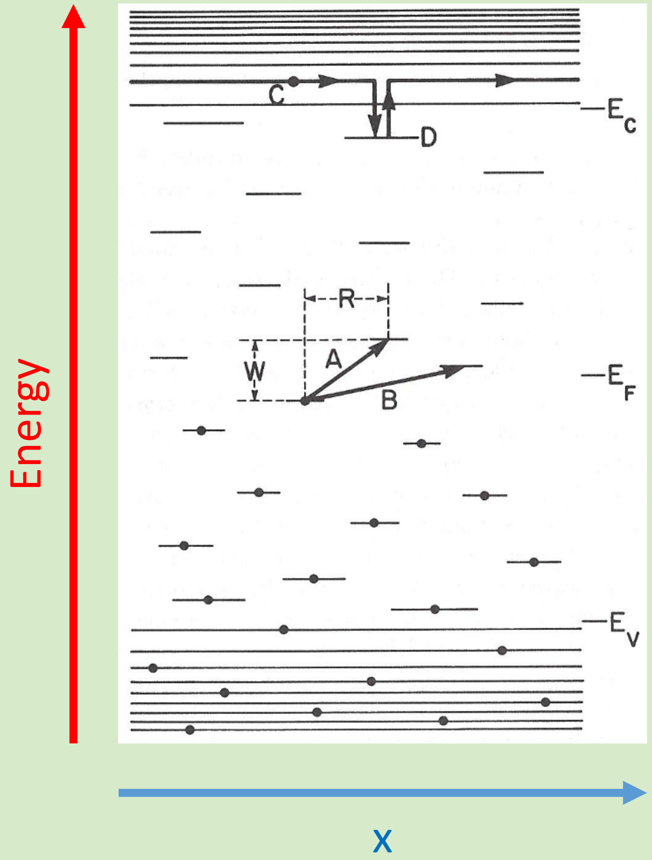
Bulk Conductivity NOT a Constant



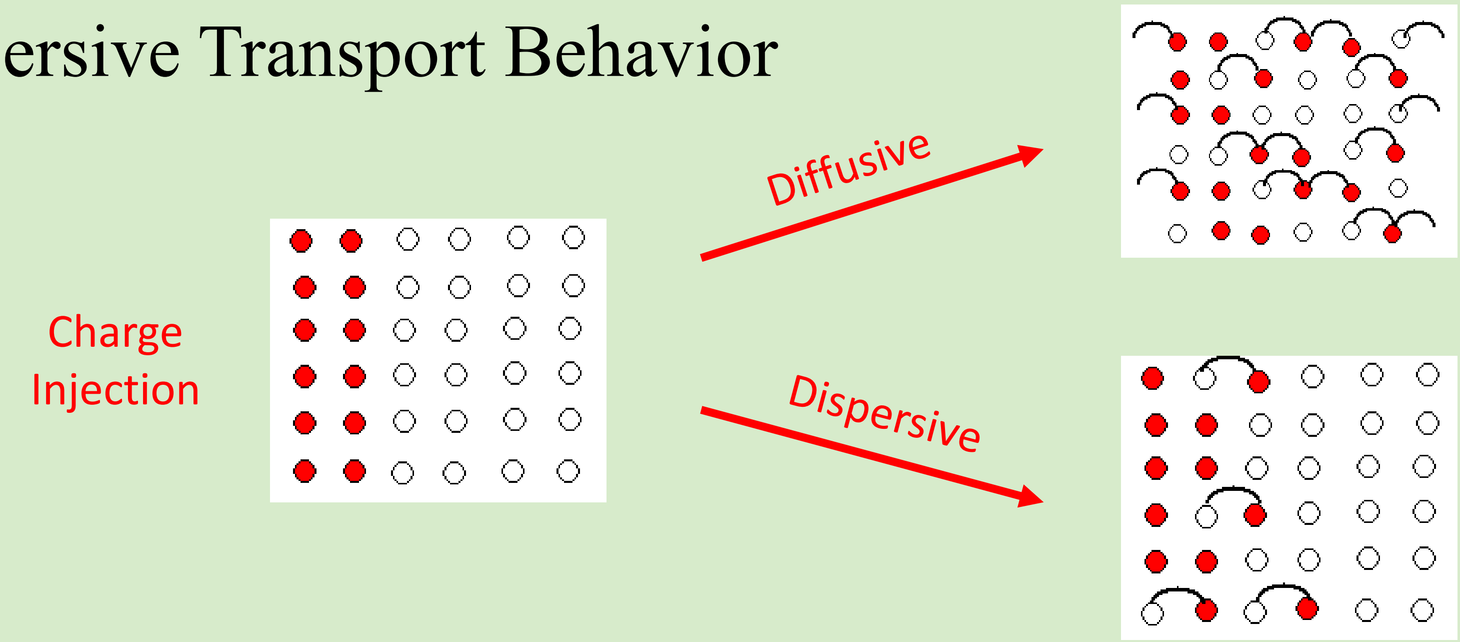
- **Transport Mechanisms in HDIM and Conductivity Model**
- **Measurement Limits and Critical Times**
- **Experimental Setup and Sample Preparation**
- **Results and Comparison**



Charge Transport in HDIM



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



R. Zalden, 'Physics of Amorphous Solids,' Ney York, Wiley (1983)

Dispersive Transport

$\sigma_{disp} t^{-(1-\alpha)}$

Pre-Transit Time

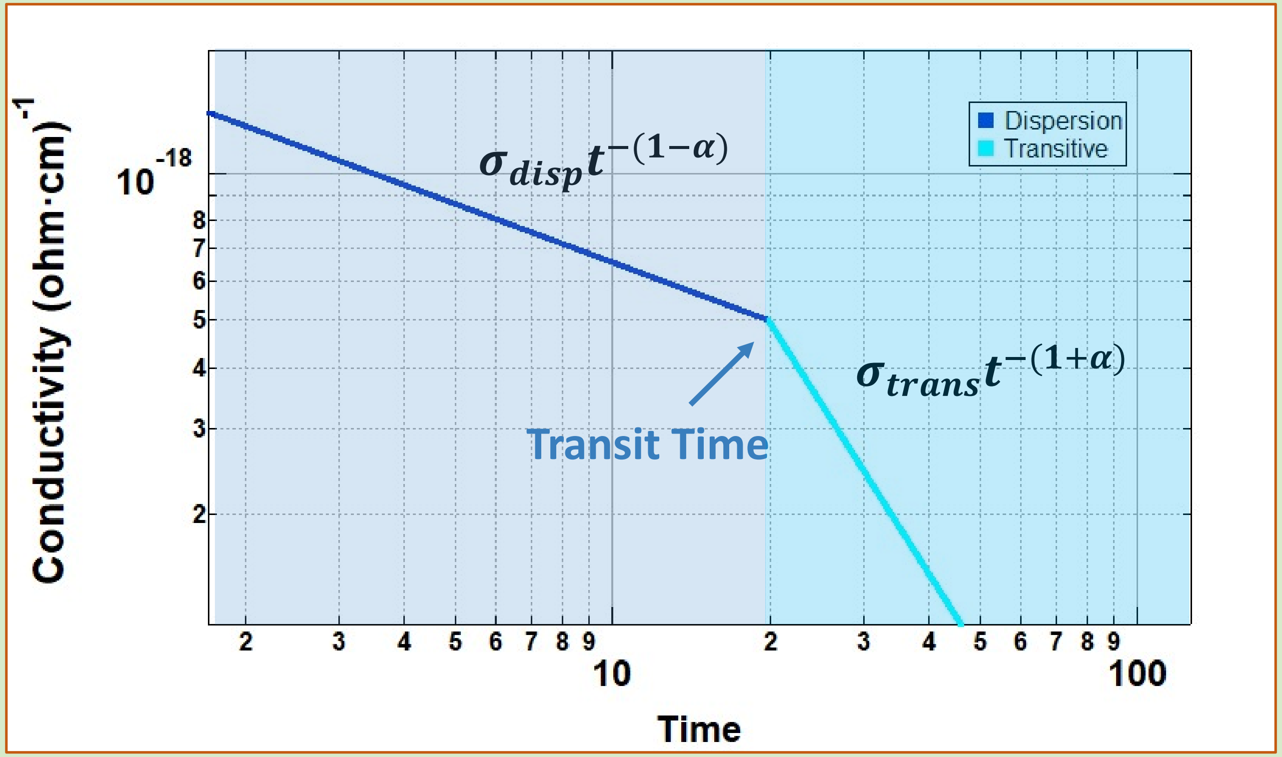
$\sigma_{trans} t^{-(1+\alpha)}$

Post-Transit Time

α dispersion parameter describing the energy width of the Density of Trap States within the mobility gap

Transit Time for Semiconductors $\sim \mathbf{10^{-5} - 10^{-2}}$ $\boldsymbol{secs}$

Transit Time for HDIM $\sim \mathbf{10^{4} - 10^{6}}$ $\boldsymbol{secs}$



R. Zallen, 'Physics of Amorphous Solids,' Ney York, Wiley (1983)

Macroscopic Charge Transport Mechanisms

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

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

- $\sigma_{DC} \equiv q_e\, n_e\, \mu_e$ **dark current or drift conduction—very long time scale equilibrium conductivity.**
- $\sigma_{pol}(t) \equiv \left[(\epsilon_r^{\infty} - \epsilon_r^{o})\epsilon_o/\tau_{pol}\right] \cdot e^{\frac{-t}{\tau_{pol}}}$ **long time exponentially decaying conduction due to polarization**
- $\sigma_{dispersive}(t) \equiv \begin{cases} \sigma^{o}_{dispersive} \cdot t^{-(1-\alpha)} & ;(\text{for } t < \tau_{transit}) \\ \sigma_{transit}(t) \equiv \sigma^{o}_{transit} \cdot t^{-(1+\alpha)} & ;(\text{for } t > \tau_{transit}) \end{cases}$ **broadening of spatial distribution of space charge through coupling with energy distribution of trap states.**
- $\sigma_{AC}(\nu) \equiv \sum_i \left[(\epsilon_r(\nu) - \epsilon_r^{o})\epsilon_o \frac{1}{1+(\nu/\nu_i)^2}\right]$

  frequency-dependent AC conduction—dielectric response to a periodic applied electric field
- $\sigma_{RIC}(t, \dot{D}; \tau^1_{RIC}, \tau^2_{RIC}) \equiv \sigma^{o}_{RIC}(\dot{D}(t))\left(1 - e^{-\tau^1_{RIC}/(t-t_{on})}\right)\left(1 + (t - t_{off})/\tau^2_{RIC}\right)^{-1}$

  radiation induced conductivity term resulting from energy deposition within the material.

Limits of Measurement and Uncertainties

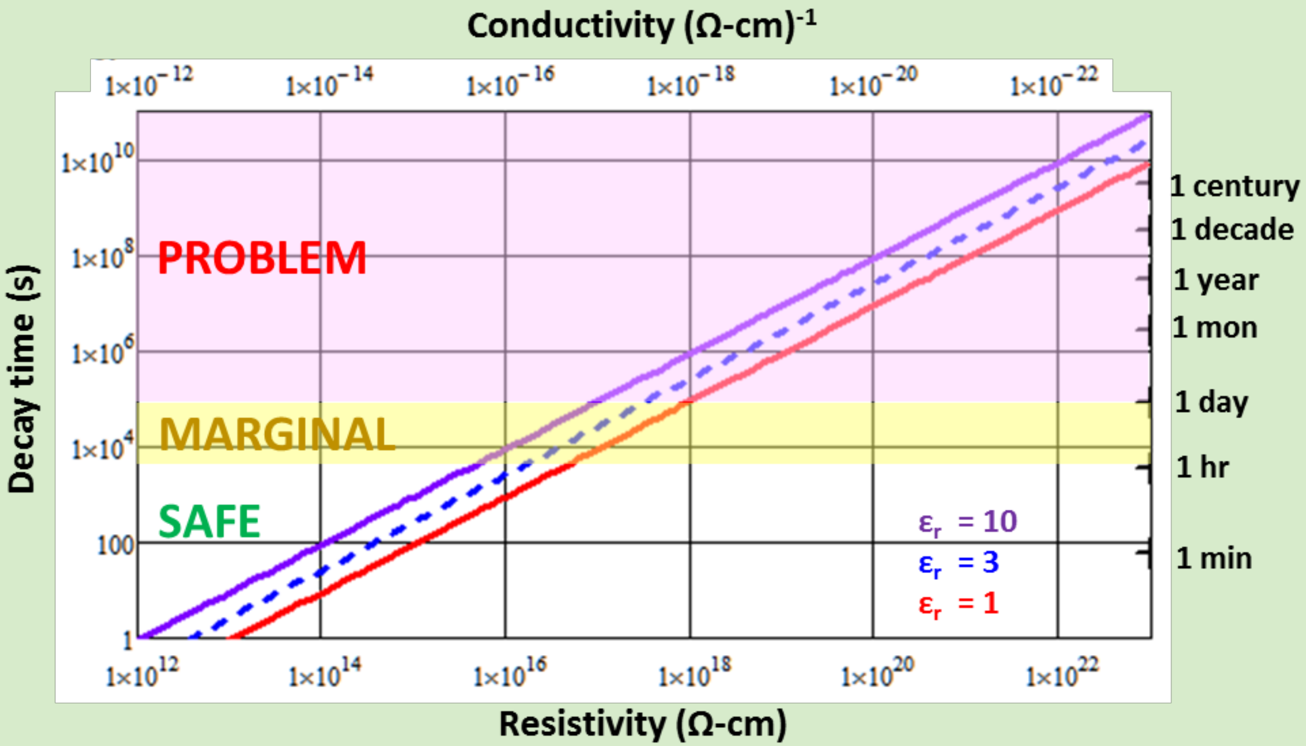
$$\sigma(t) = \sigma_{DC} + \sigma_{pol} e^{-(\frac{t}{\tau_{pol}})} + [\sigma_{disp} t^{-(1-\alpha)} + \sigma_{trans} t^{-(1+\alpha)}] + \sigma_{AC} + \sigma_{RIC}$$

CVC

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

Noise Sources	Estimated Contributions to Conductivity
• Thermal	• $\Delta I_{JN} \approx 4x10^{-18} A \rightarrow\rightarrow \sigma \approx 6x10^{-24} (\Omega \cdot cm)^{-1}$
• σ_{AC}	• Displacement current due to voltage ripple $\rightarrow\rightarrow \Delta V \approx 0.02\%$ **(Battery)**
• σ_{RIC}	• RIC from cosmic microwave background for LDPE $\rightarrow\rightarrow \sigma \approx 4x10^{-23} (\Omega \cdot cm)^{-1}$
• Electrometer Noise	• $\Delta I \approx 2x10^{-15} A \rightarrow\rightarrow \sigma \approx 3x10^{-21} (\Omega \cdot cm)^{-1}$

Critical Time Scales and Conductivities



Corresponding Resistivities $(\varepsilon_r = 1)$

1 min → ρ•ε_o $\sim 1x10^{-15}(\Omega \cdot cm)^{-1}$

1 hr → ρ•εo $\sim 3x10^{-17}(\Omega \cdot cm)^{-1}$

1 day → ρ•ε_o $\sim 1x10^{-18}(\Omega \cdot cm)^{-1}$

Limit------>~1 yr → ρ•ε_o $\sim 3x10^{-21}(\Omega \cdot cm)^{-1}$

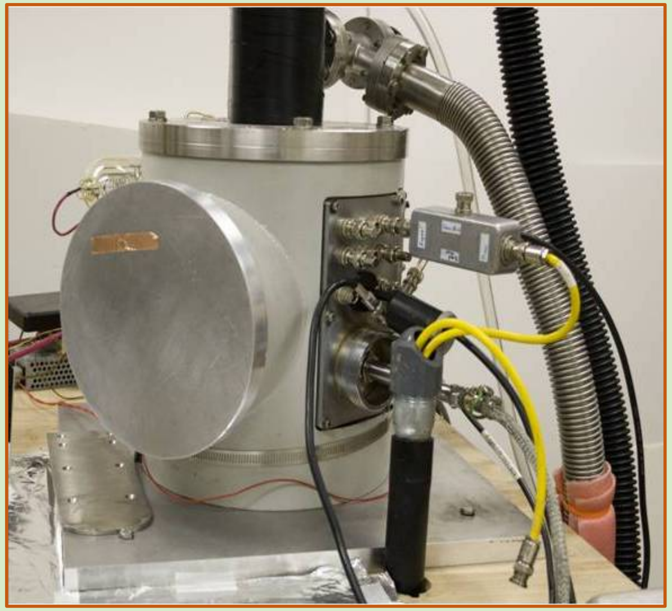
15 yr → ρ•ε_o $\sim 2x10^{-22}(\Omega \cdot cm)^{-1}$

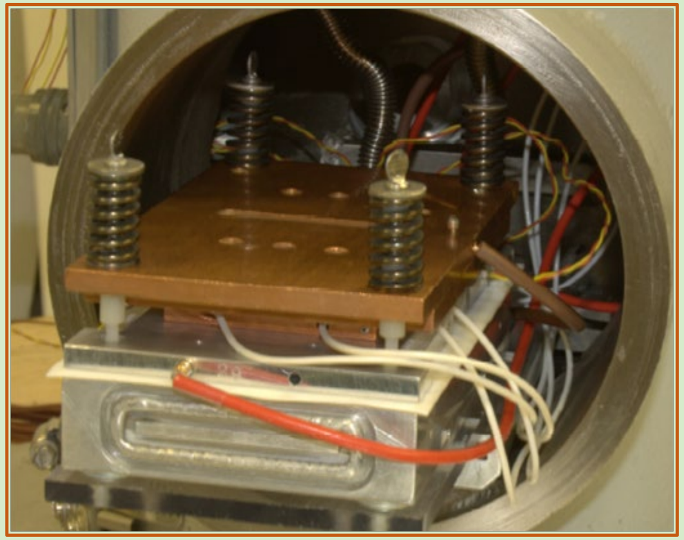
500 yr → ρ•εo $\sim 1x10^{-24}(\Omega \cdot cm)^{-1}$

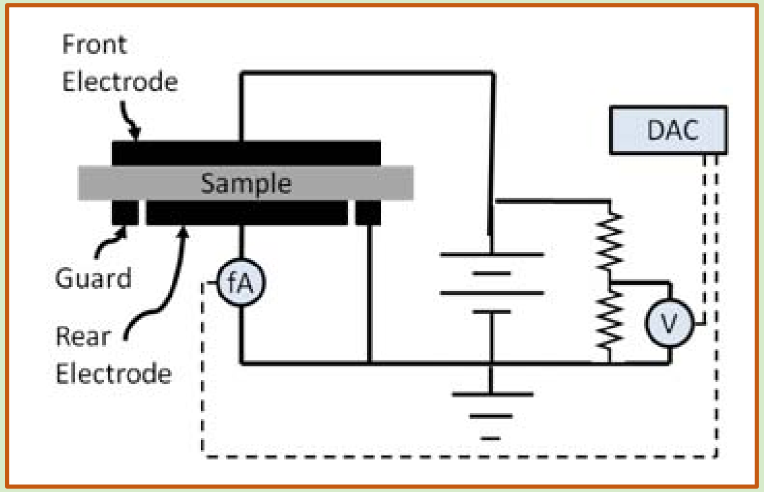
$$\tau_{decay} = \frac{\varepsilon_0 \varepsilon_r}{\sigma}$$

$$\tau_Q < \tau_{pol} < \tau_{transit} < \tau_{decay} < \tau_{eq} < \tau_{exp}$$

CVC Experimental Setup







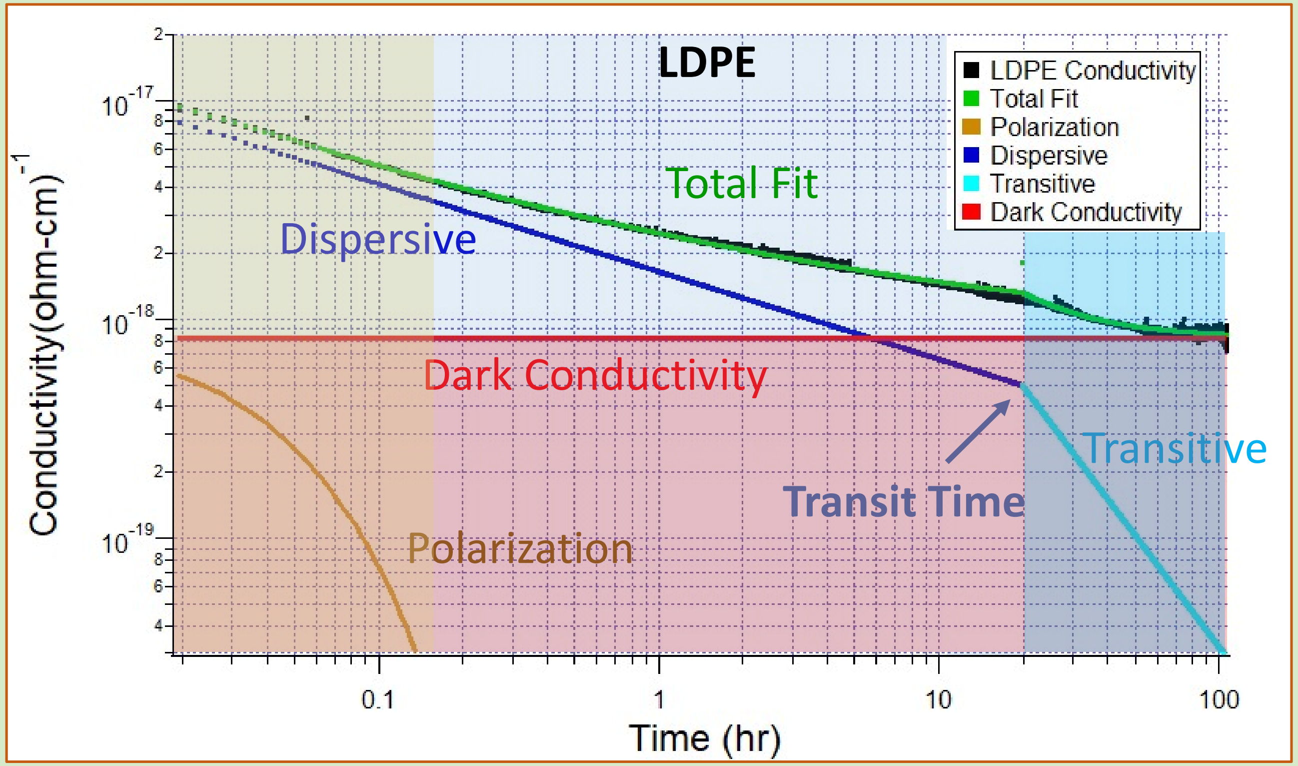
Constant Voltage Conductivity

- Time evolution of conductivity
- $<10^{-1}$ s to $>10^{6}$ s
- $\pm\, 2x10^{-15} A$ resolution
- $\Delta I \approx 3x10^{-16}\ A$
- $\sim 100\ K\ < T\ < 375\ K$

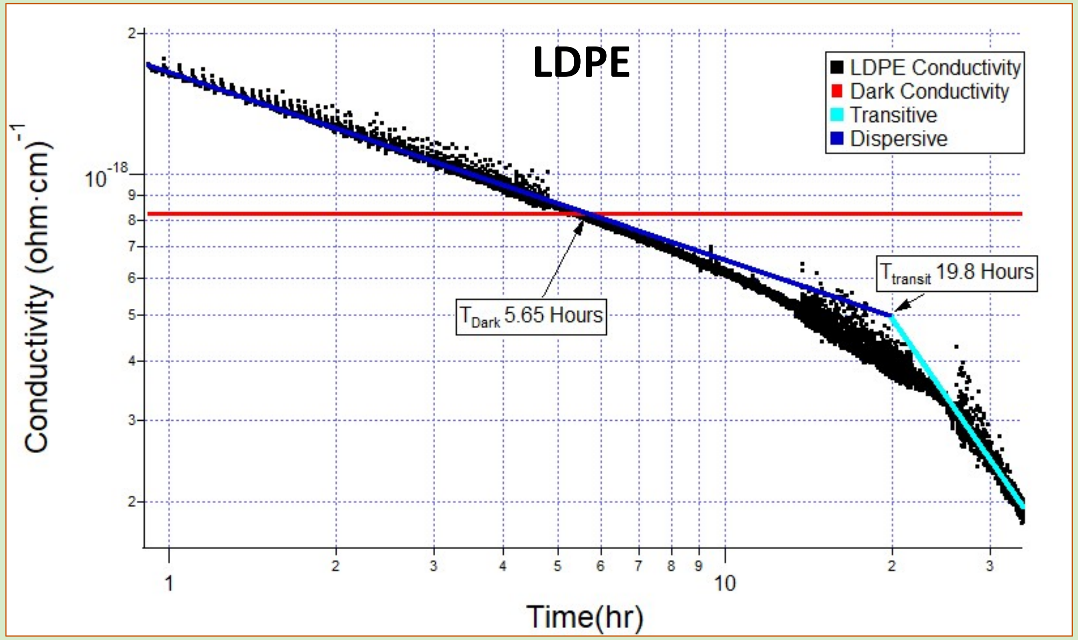
$$\sigma(t) = \frac{J(t)}{F(t)} = \frac{I(t) \cdot d}{V(t) \cdot A}$$

$V(t) \rightarrow V$ with Battery

LDPE Results



Removing DC from the data exposed the *'Kink'*



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

$\sigma_{DC} = 8.4 \pm 0.3 \text{ x} 10^{-19} (\Omega \cdot cm)^{-1}$ @ 23.9℃

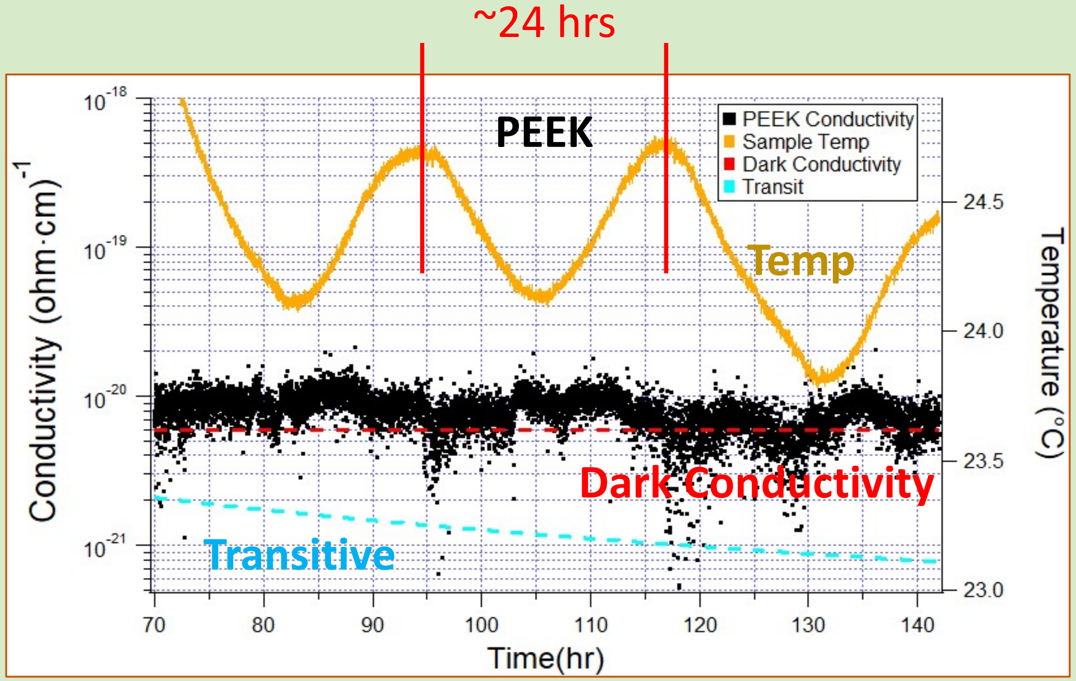
$\sigma^{0}_{pol\,1} = 9.0x10^{-19} (\Omega \cdot cm)^{-1}$

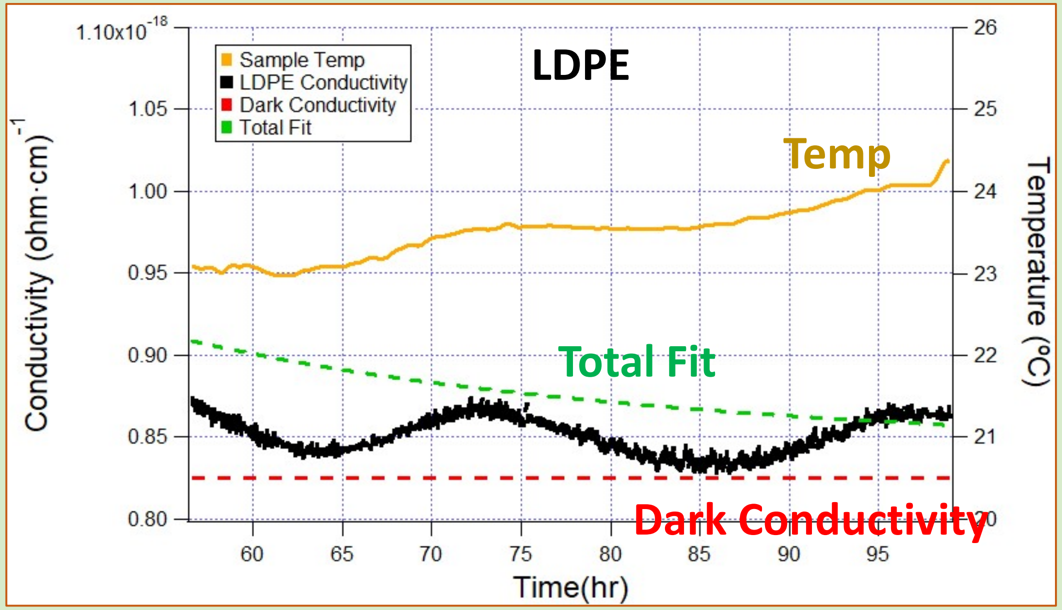
$\tau_{pol} = 2.4\, min$

Transit Time = 20.5 hours

α = 0.6

Determining Equilibrium Conductivity

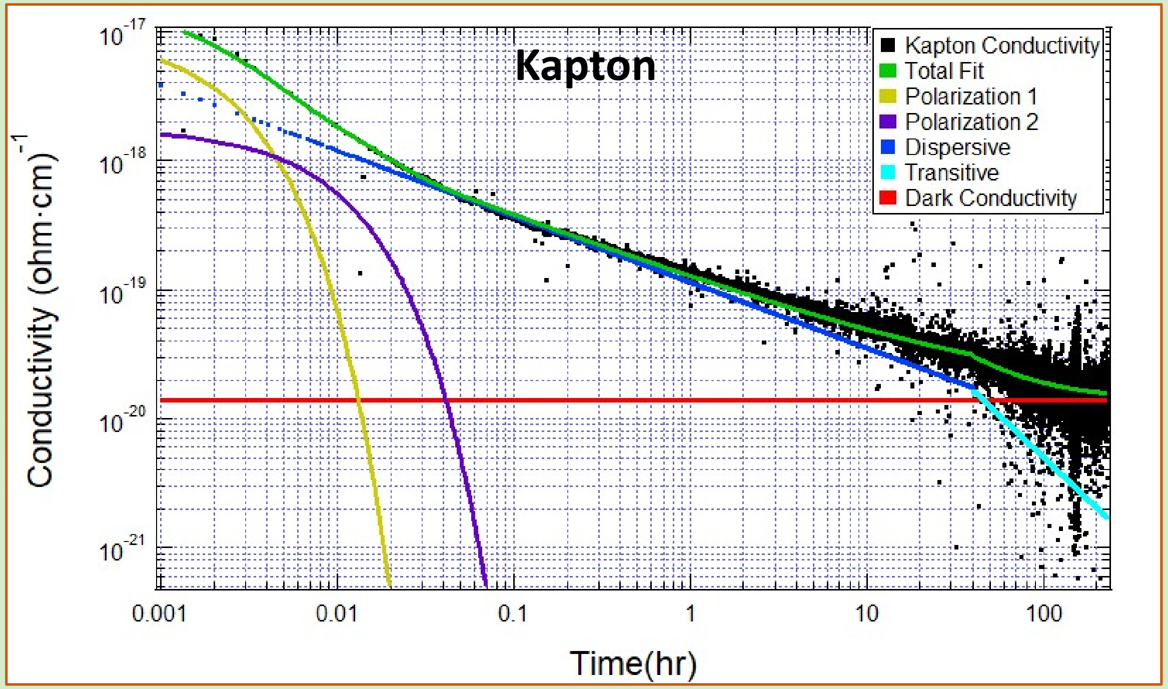


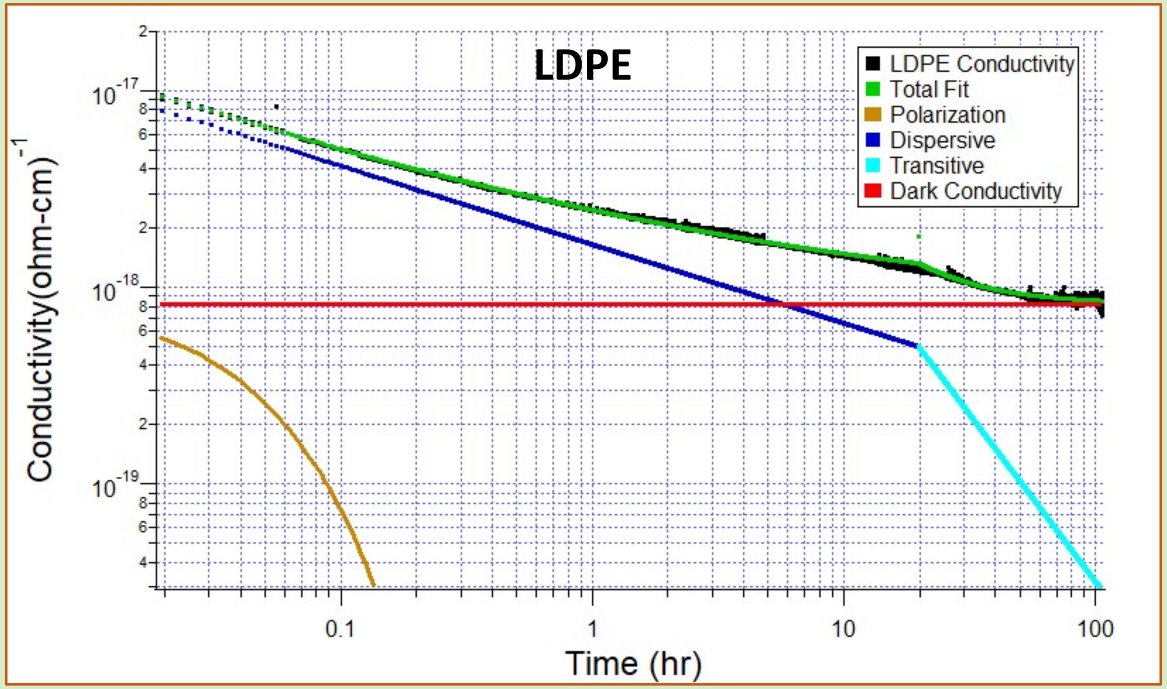


Averages of conductivity taken near end at the same temperature over cycles

Equilibrium defined as when the transitive contribution falls below instrument error and when the total fit agrees with the dark conductivity

Results: Kapton vs LDPE





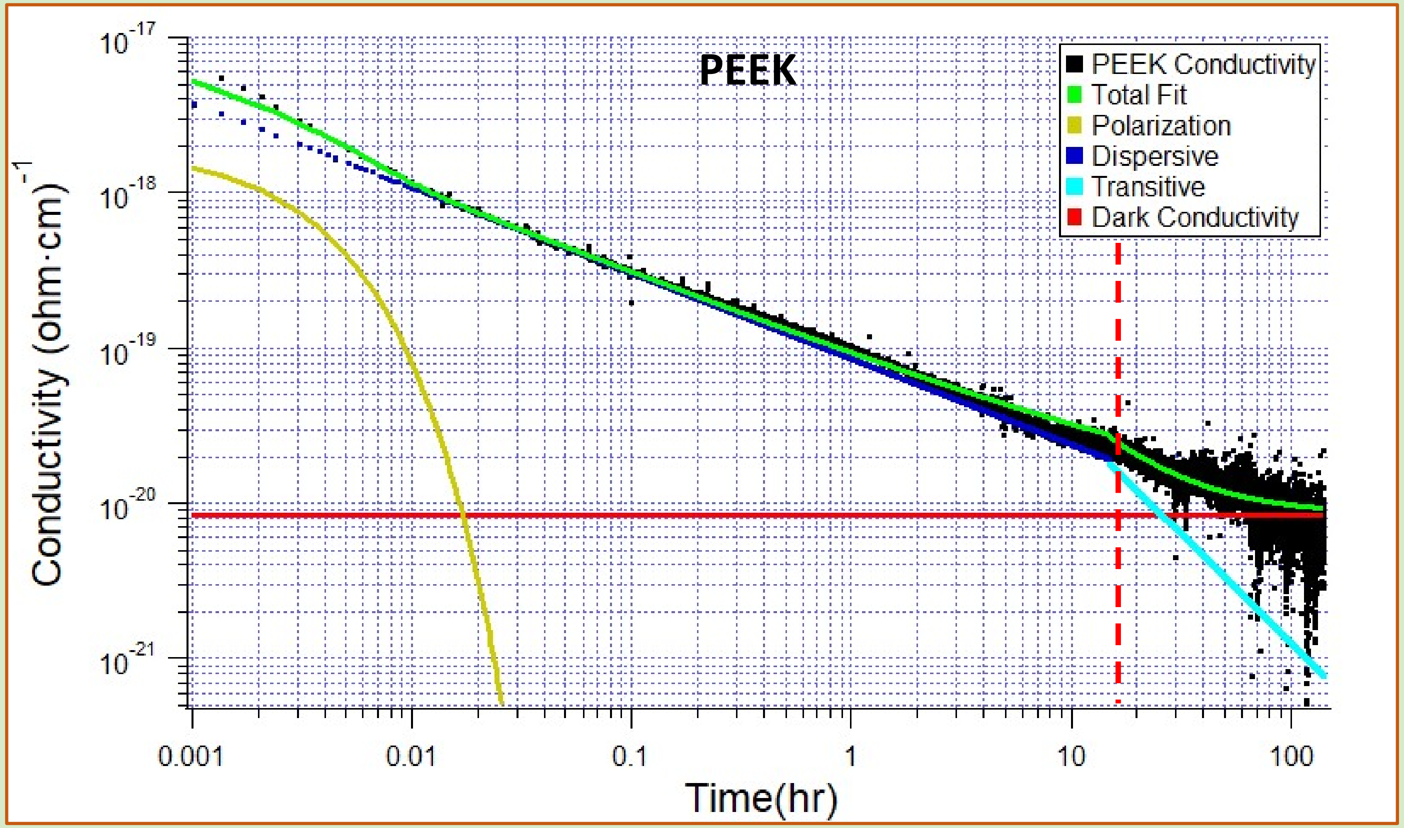
2 polarization contributions of greater magnitude but smaller time constant than LDPE

$$\sigma^0_{pol\,1} = 1.0x10^{-17}(\Omega \cdot cm)^{-1} \quad \tau_{pol\,1} = 0.1\,min$$

$$\sigma^0_{pol\,2} = 1.8x10^{-18}(\Omega \cdot cm)^{-1} \quad \tau_{pol\,2} = 0.5\,min$$

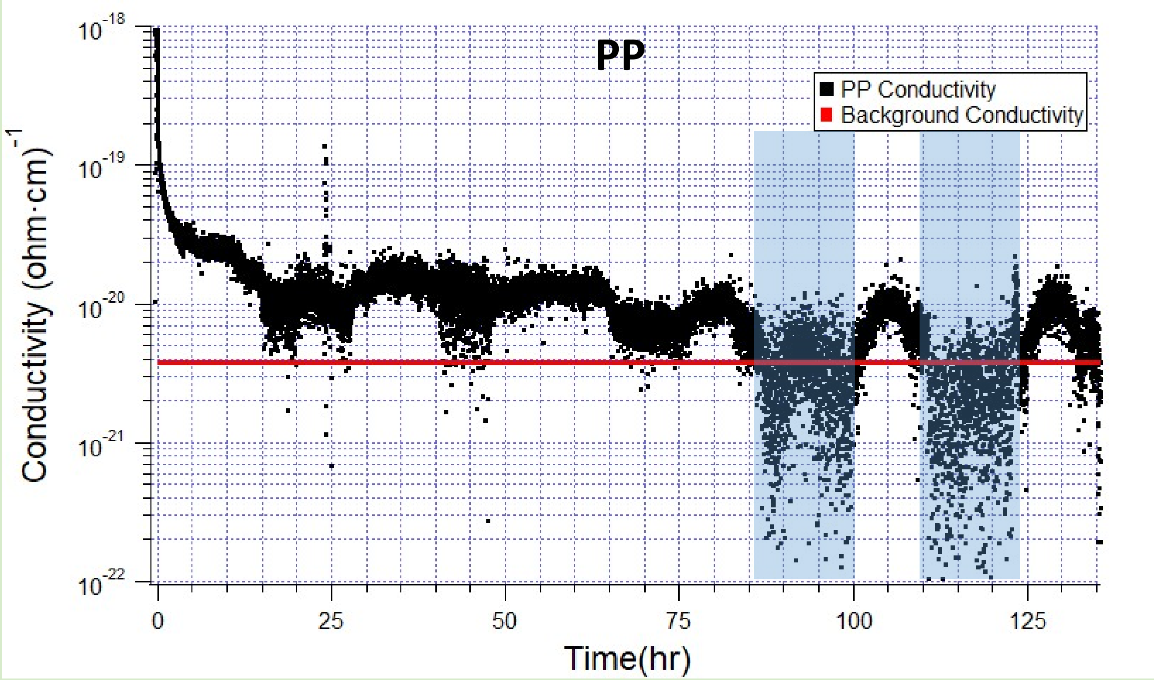
$$\sigma^0_{pol\,1} = 9.0x10^{-19}(\Omega \cdot cm)^{-1} \quad \tau_{pol} = 2.4\,min$$

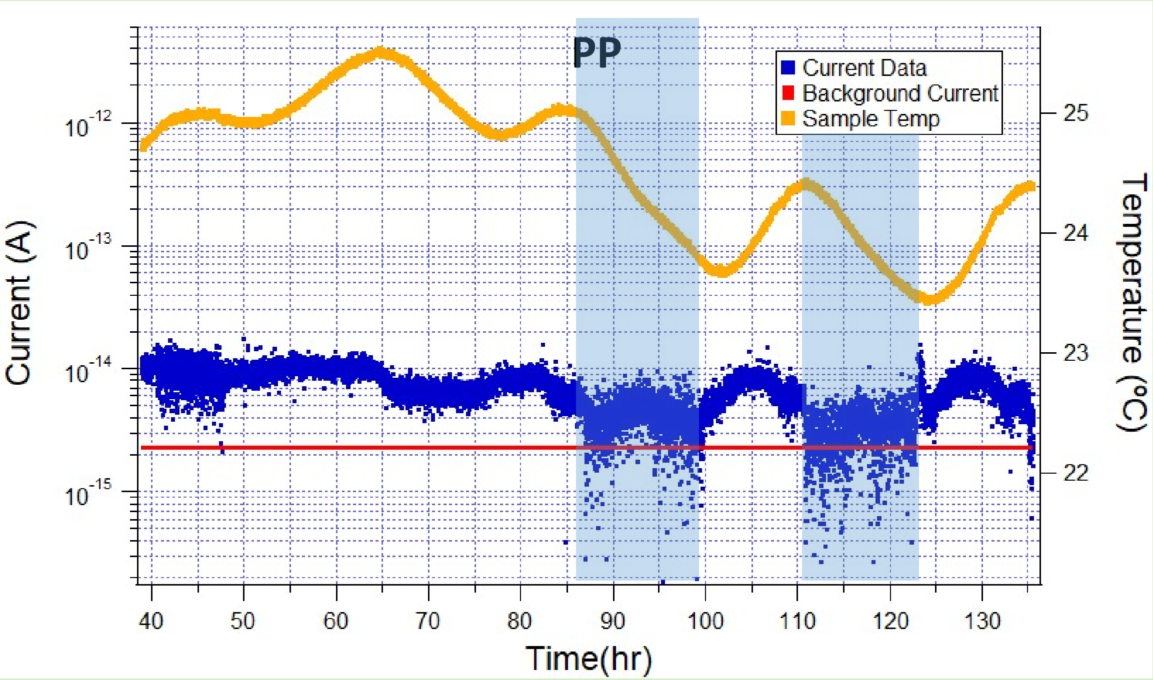
PEEK Results



- 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 $\sigma_{DC} \sim 3x10^{-18}(\Omega \cdot cm)^{-1}$
- Very Long Equilibrium Time

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