Measuring and Modeling the Conductivity of Highly Insulating Materials

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I. Introduction and Experiment

The Constant Voltage Conductivity (CVC) chamber (Figure 1) of the Utah State University Materials Physics Group (MPP) is used to measure the conductivity of highly disordered insulating polymers. In this experiment, samples of low density polyethylene (LDPE) and Kapton® or polyimide (PI), were placed between two parallel plate electrodes while a constant electric field was applied from a battery voltage source (420 V to 780 V). From the resulting current, i, the conductivity, α, was calculated using the expression

\[ \sigma = \frac{i}{E} \frac{d}{\sqrt{A}} \]

(1)

where d is the sample thickness, V is the applied voltage, and A is the electrode area. Lastly, the time-dependent conductivity was fit with a multi-process, physics-based model of conductivity to characterize the distribution of atomic-scale defects in the highly disordered insulating materials studied.

These measurements provide baseline conductivity and charge decay times useful for determining spacecraft charging effects in materials regularly used in space.

Figure 1 – CVC Assembly
Left: Electrical schematic of the CVC chamber [1].
Right: Picture of CVC chamber [2].

II. Conductivity Theory

To understand the macroscopic behavior of materials, it is necessary first to understand how they behave at the microscopic level. In general, materials can be classified as conductors, semiconductors, and insulators based on how charge moves through them. This is determined by the size of the material’s band gap (Figure 2). In insulators, the band gap is wide so that electrons cannot move easily from the valence to the conduction band. Disorder in materials creates localized, or “trap,” states within the gap. Electrons can move in the forbidden area of the band gap by hopping between these states (Figure 2).

Equation (2) models the time-dependent conductivity in the polymers [1]:

\[ \sigma_{total}(t) = \sigma_{Sat} + \sigma_{diff} t^{-(1+\alpha)} (t_{trans} - t) \]

(2)

- Saturation, or dark, conductivity (\(\sigma_{Sat}\)) is a constant, equilibrium conductivity and is reached at long time scales.
- Polarization conductivity (\(\sigma_{pol}\)) is a combination of effects due to the material’s response to an applied electric field.
- Diffusive conductivity (\(\sigma_{diff}\)) results from movement of the centroid of the charge distribution through the material with time.
- Dispersive (\(\sigma_{disp}\)) and transit (\(\sigma_{trans}\)) conductivity both describe the distortion of spatial charge distribution because of disorder in the material (Figure 3). Dispersive conductivity is active before the time \(t_{trans}\), when the charge front reaches the edge of the material. The transit conductivity dominates after \(t_{trans}\) until the material reaches equilibrium.
- \(\alpha\) is indicative of the width of trap state energy distribution [1].

Figure 2 – Disordered band structure [3].

Figure 3 – Diffusive vs. Dispersive Transport [3].

III. Results

<table>
<thead>
<tr>
<th>Fitting Coefficients</th>
<th>PI</th>
<th>LDPE</th>
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<tbody>
<tr>
<td>(\sigma_{Sat})</td>
<td>1.0 x 10^{-15} \Omega \cdot m</td>
<td>1.0 x 10^{-15} \Omega \cdot m</td>
</tr>
<tr>
<td>(\sigma_{diff})</td>
<td>1.0 x 10^{-2} \Omega \cdot m</td>
<td>1.0 x 10^{-2} \Omega \cdot m</td>
</tr>
<tr>
<td>(\sigma_{pol})</td>
<td>1.0 x 10^{-5} \Omega \cdot m</td>
<td>1.0 x 10^{-5} \Omega \cdot m</td>
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Table 1 – Data fitting coefficients

Figure 4 – PI conductivity vs. time: log-log plot

Figure 5 – PI conductivity vs. time: linear plot

Figure 6 – LDPE conductivity vs. time: log-log plot

Figure 7 – LDPE conductivity vs. time: linear plot

IV. Conclusions and Future Work

Conclusions:
- The model of conductivity in (2) fits both data sets well.
- According to the model of conductivity used, \(\sigma_{sat}\) should equal \(\sigma_{pol}\). This is true within acceptable error for the PI and LDPE data shown, lending credence to the model in (2).
- \(\alpha\) is also a measure of the material’s disorder. Thus, it was expected that PI would have a larger \(\alpha\). LDPE having a larger \(\alpha\) may be due to temperature effects.
- The fit is least accurate for the polarization region and subsequent curve in the data. This is understandable because multiple different polarization processes are taking place, not simply one as supposed by (2).
- Long time scales, far longer than anticipated, are required to measure the conductivity accurately and capture the different conductivity mechanisms. Charge fronts can take from 25 to 40 hours to travel 25 μm.

Future work:
- Improving the conductivity model by including a more complex description of polarization. This should include more of the diverse physical mechanisms occurring in polarization.
- Testing temperature dependence of conductivity.
- Testing the conductivity of irradiated samples.

References