Gaseous Detector Resistive Plates beyond the RC Paradigm

Microscopic Conduction Dynamics and High-Rate Voltage Drop in RPCs

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September 2026

Outline

1. Motivation & Experimental Setup
2. Room Temperature Dynamics
3. Temperature Dependence
4. Conclusions

Motivation: RPCs and the High-Rate Challenge

- Resistive Plate Chambers (RPCs) offer excellent time resolution in high-energy physics.
- **High-rate operation:** Particle flux (Φ) injects charge that must be evacuated through the plates.
- Charge evacuation generates a voltage drop: $V_{\text{effective}} = V_{\text{applied}} - \Delta V_{\text{plate}}$.
- High ΔV_{plate} collapses the electric field, drastically reducing rate capability and efficiency.

Key Magnitudes to Predict

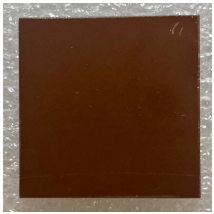
1. **Steady-state ΔV_{plate}:** Governed mainly by $\rho_{\text{DC}} \cdot \Phi$ (the standard 'DC model').
2. **Spread in steady state:** Relative fluctuation $\sigma(\Delta V)/\langle \Delta V \rangle \sim 1/\sqrt{\tau}$, where τ is the recovery time[cite: [1], [2], [5]].
3. **Time to reach steady state (t_{eq}):** Directly proportional to τ[cite: [3], [4], [5]].

The Core Problem: Standard models assume an ideal RC circuit ($\tau \approx \rho_{\text{DC}} \cdot \varepsilon_0 \varepsilon_\infty$), completely ignoring dielectric relaxation processes. **This work aims to fill this gap.**

Resistive Materials in Particle Physics

We studied four representative materials:

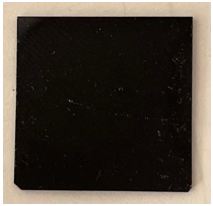
- **Standard Bakelite:** Historically used in ATLAS and CMS at the LHC ($\rho \sim 10^{10} - 10^{12}\ \Omega \cdot \text{cm}$).
- **Float Glass (silicate glass):** High precision reference for TOF systems in ALICE and HADES ($\rho \sim 10^{12}\ \Omega \cdot \text{cm}$).
- **Chinese & 'Crispin' Glass:** Low-resistivity glass ($\rho \sim 10^{10}\ \Omega \cdot \text{cm}$) developed for next-generation high-rate RPCs (e.g., CBM at FAIR).



Bakelite



'Crispin' Glass



Chinese Glass



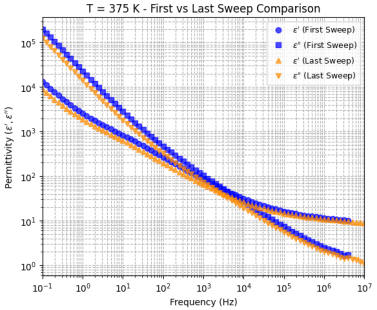
Float Glass

Experimental Protocol and Setup

Measurements performed at the Materials Physics Center (CFM) in Basque Country.

- **Equipment:** Novocontrol Alpha-A (10^{-1} to 10^{7} Hz) for AC, Keithley 6517B for DC (100 V step).
- **Dehydration:** High vacuum thermal baking ($350 - 400$ K) is critical to remove artificial surface ionic paths in Bakelite.
- **Electrodes:** Cr (100 nm, baseline reference) vs. Ag paint to evaluate interface effects.(Note: Cr is assumed for all subsequent measurements unless Ag is specified).





Room Temperature conductivity: DC and KK analysis

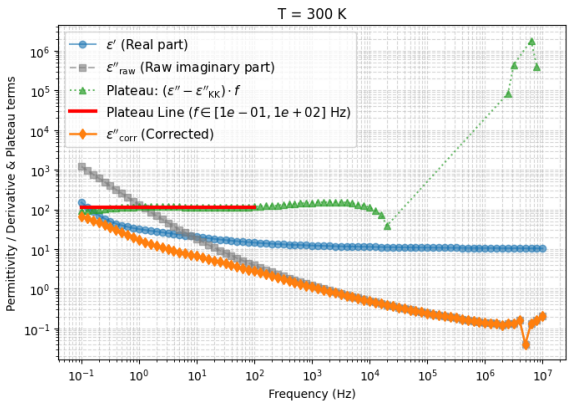
- **Real Part (ε'):** Experimental permittivity baseline.
- **Kramers-Kronig (ε''_{KK}):** Ohmic loss-free spectrum derived via derivative approximation:

$$\varepsilon''_{KK} \approx -k \frac{d\varepsilon'}{d \log_{10} f} \qquad k \in (0.68 - 0.77)$$

- **DC Conduction Plateau:** Isolate conduction to extract resistivity (ρ_{DC}):

$$\text{Plateau} = (\varepsilon'' - \varepsilon''_{KK}) \cdot f = \frac{1}{2\pi\varepsilon_0\rho_{DC}}$$

- **Loss Correction (ε''_{corr}):** Subtracting the ohmic term isolates pure dipolar relaxation.

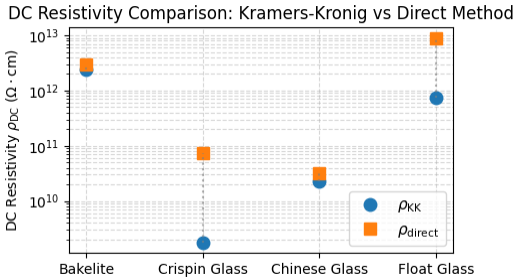


Conduction plateau identification and ε''_{corr} extraction at $T = 300$ K. (Chinese glass with Cr.)

DC Resistivity: Direct vs. Kramers-Kronig Method

- **High Correlation:** Bakelite and Chinese Glass show excellent consistency between both methods within the same order of magnitude.
- **Discrepancies:**
  - **Float Glass:** Shows a deviation of ~ 1 order of magnitude.
  - **Crispin Glass:** Exhibits a larger shift (~ 1.5 orders of magnitude).

Material	ρ_{KK} $(\Omega \cdot \text{cm})$	ρ_{direct} $(\Omega \cdot \text{cm})$
Bakelite	2.410×10^{12}	3.031×10^{12}
Crispin Glass	1.755×10^{9}	7.424×10^{10}
Chinese Glass	2.283×10^{10}	3.159×10^{10}
Float Glass	7.549×10^{11}	9.042×10^{12}



Logarithmic comparison of DC resistivity values extracted via Kramers-Kronig analysis vs. direct measurement.

Fit Methodology: Selecting the Dielectric Model

Comparing standard mathematical models:

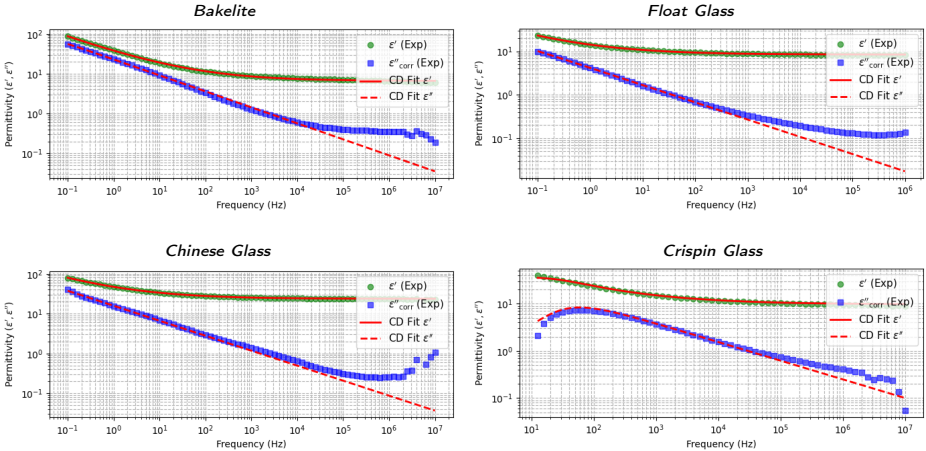
- **Debye:** Single relaxation time (fails in disordered glasses).
- **Cole-Cole:** Symmetric broadening (α).
- **Cole-Davidson (CD):** Asymmetric broadening (β), where $0 < \beta \leq 1$.

Cole-Davidson Formula

$$\varepsilon^*(\omega) = \varepsilon_\infty + \frac{\Delta\varepsilon}{(1 + i\omega\tau_{\text{CD}})^\beta}$$

Observation: CD accurately reproduces the asymmetric broadening observed in the dielectric relaxation spectra.

Validation of the Cole-Davidson Model



Conclusion: The Cole-Davidson model describes well the dielectric relaxation process across all tested materials.

Extracted Cole-Davidson Parameters

- **Direct Projection:** Fitted parameters ($\Delta\varepsilon$, τ_{CD}, β) extracted from ε'' are projected directly onto ε' without modifications.
- **Consistency:** Agreement across all four materials and electrode types (Ag and Cr), generally, much less than a factor x2 deviation.
- **Model Input:** These obtained parameters will be used in subsequent time-domain and transient voltage simulations.

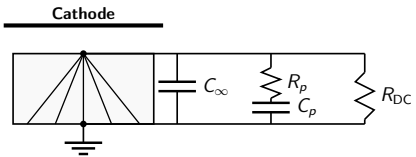
Cole-Davidson Fit Results

Material	ε_∞	$\triangle\varepsilon$	τ_{CD} (s)	β
Bakelite Cr.	6.575	291.850	24.460	0.401
Bakelite Ag.	9.515	317.877	27.650	0.430
Crispin Cr.	9.715	27.076	0.006	0.396
Crispin Ag.	19.841	20.216	0.003	0.464
Chinese Glass Cr.	15.232	346.591	40.513	0.416
Chinese Glass Ag.	23.309	207.669	32.492	0.371
Float Glass Cr.	8.419	58.636	32.048	0.397
Float Glass Ag.	11.158	47.522	29.867	0.314

Physical Analysis: Debye vs. Cole-Davidson

Standard Debye Model

$i(t) = q \cdot \delta(t)$ $\quad \frac{\Delta V_{\text{pol}}(t)}{q/C_s} = 1 - e^{-t/\tau_{\text{DB}}}$



- **Single Relaxation Time (τ_{DB}):**

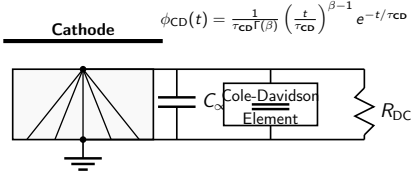
$$\frac{\Delta V_{\text{pol}}(t)}{q/C_s} = 1 - \phi_{\text{Debye}}(t)$$

where $\phi_{\text{Debye}}(t) = e^{-t/\tau_{\text{DB}}}$.

Cole-Davidson Network

$i(t) = q \cdot \delta(t)$ $\quad \frac{\Delta V_{\text{pol}}(t)}{q/C_s} = 1 - \phi_{\text{CD}}(t)$

$\phi_{\text{CD}}(t) = \frac{1}{\tau_{\text{CD}}\Gamma(\beta)} \left(\frac{t}{\tau_{\text{CD}}}\right)^{\beta-1} e^{-t/\tau_{\text{CD}}}$



- **Continuous Relaxation Spectrum (τ_{CD}, β):**

$$\frac{\Delta V_{\text{pol}}(t)}{q/C_s} = 1 - \phi_{\text{CD}}(t)$$

where $\phi_{\text{CD}}(t) = \mathcal{F}^{-1}\left[\frac{1}{(1+i\omega\tau_{\text{CD}})^{\beta}}\right]$.

- **Direct RC ($\tau_{RC,\mathbf{dir}}$):** Simple RC time constant from direct capacity (ε' at high f) and DC resistivity (ρ_{DC}).
- **KK-Derived RC ($\tau_{RC,\mathbf{KK}}$):** RC time constant using parameters derived via Kramers-Kronig relations.
- **CD Operational ($t_{1/e}$):** Decay time to $1/e$ in the Cole-Davidson model. Enables direct comparison with simple RC models:

$$\frac{\Gamma(\beta, t_{1/e}/\tau_{\mathrm{CD}})}{\Gamma(\beta)} = \frac{1}{e}$$

- **CD Physical Mean ($\langle\tau\rangle$):** Average relaxation time of the distribution:

$$\langle\tau\rangle = \beta \cdot \tau_{\mathrm{CD}}$$

Full Dataset Overview

Material	$\tau_{\mathrm{RC,dir}}$	$\tau_{\mathrm{RC,KK}}$	$t_{1/e}$	$\langle\tau\rangle$
Bak.	2.125	2.174	7.040	9.808
Crispin	0.065	0.001	0.002	0.002
Ch. G.	0.071	0.023	12.371	16.848
F. G.	6.501	0.610	5.587	9.367

Electrode Effect (Bakelite)

Sample	$\tau_{\mathrm{RC,dir}}$	$\tau_{\mathrm{RC,KK}}$	$t_{1/e}$	$\langle\tau\rangle$
Cr.	2.125	2.174	7.040	9.808
Ag.	2.006	1.499	8.876	11.851

All relaxation times are reported in seconds (s).

KEY RESULT 1: Voltage Relaxation Electrode Interface

Polarization Voltage Dynamics $V_{\mathbf{pol}}(t)$:

- **Cole-Davidson (Full Relaxation):**

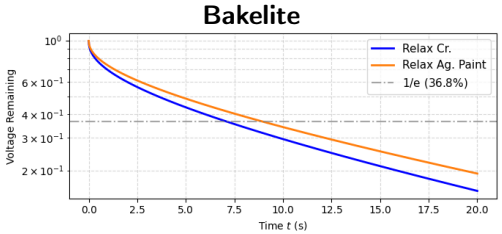
$$V_{\text{pol}}(t) = 1 - \int_0^t \Phi(t')\, dt'$$

- **Direct RC Fit ($RC_{\mathbf{dir}}$):**

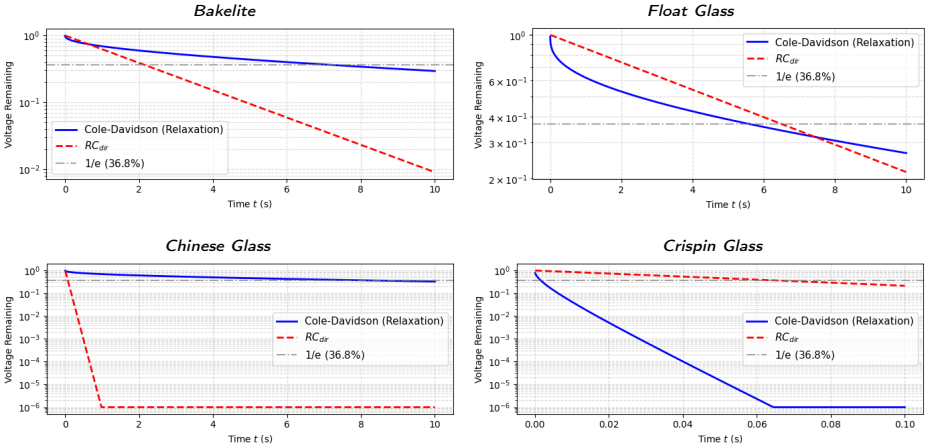
$$V_{\text{RC}}(t) = e^{-t/\tau_{\mathbf{RC,dir}}}$$

Electrode Impact:

- High consistency between evaporated Cr (100 nm) and Ag paint.
- Confirms that relaxation dynamics are **bulk-dominated**, not contact-driven.



KEY RESULT 1: *RC* Model Validity Across Materials



- **Fast dynamics ($\tau_{\mathbf{RC,dir}} \ll \tau_{\mathbf{relax}}$):** Strong non-exponential tails cause major deviations, requiring CD correction.
- **Slow dynamics ($\tau_{\mathbf{RC,dir}} \gtrsim \tau_{\mathbf{relax}}$):** The simple *RC* exponential closely tracks experimental data.

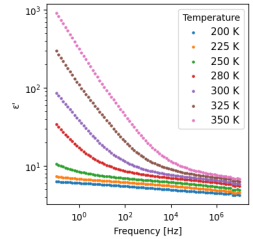
Motivation for Temperature (T) Studies

- **Question:** If RPCs operate at room temperature, why study T dependence?
- **Answer:** Temperature sweeps are the only physical tool to thermally activate charge carriers in the volume.

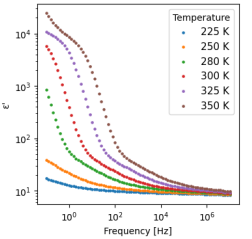
Goals of Temperature Studies

1. Extract the Activation Energies (E_a).
2. Separately study DC conduction and AC polarization.
3. Evaluate whether both processes share a common microscopic origin.

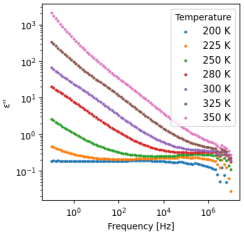
Temperature Spectroscopy and Electric Modulus (M'')



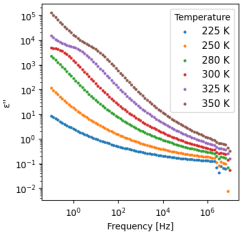
Bakelite



Crispin Glass



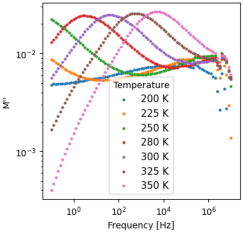
Bakelite



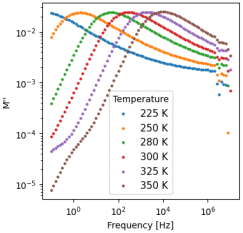
Crispin Glass

Why Electric Modulus?

- σ_{DC} hides ε'' peaks.
- Formula: $M'' = \frac{\varepsilon''}{\varepsilon'^2 + \varepsilon''^2}$
- Suppresses DC background to reveal clean peaks for $\omega_{max}(T)$.

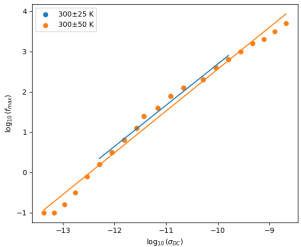


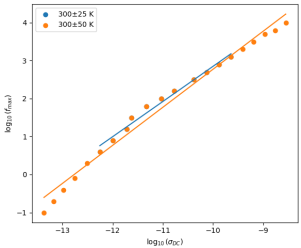
Bakelite

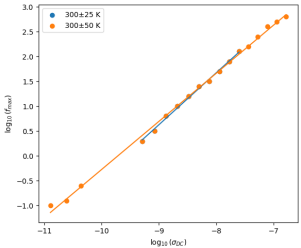


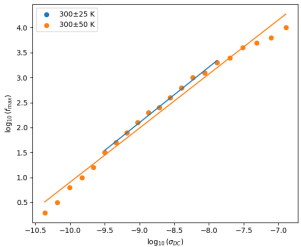
Crispin Glass

Barton–Nakajima–Namikawa (BNN) Relation









Empirical Relation

$$\sigma_{DC} \propto f_{\max}$$

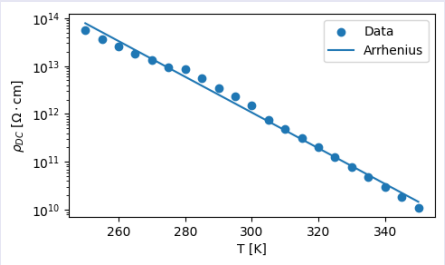
If conduction and relaxation are correlated, both quantities exhibit an approximately linear relationship.

Material	m	R^2
Bakelite (Ag.)	0.95	0.99
Bakelite (Cr.)	1.02	0.98
Crispin Glass	0.97	0.99
Chinese Glass	1.01	0.99

Characterization via the Arrhenius Law

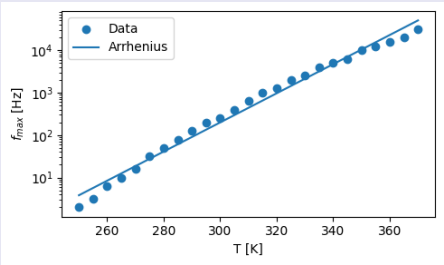
Conduction

$$\rho_{DC} = \rho_0 \exp\left(\frac{E_a^{cond}}{k_B T}\right)$$



Relaxation

$$f_{\max} = f_0 \exp\left(-\frac{E_a^{rel}}{k_B T}\right)$$



Key Idea

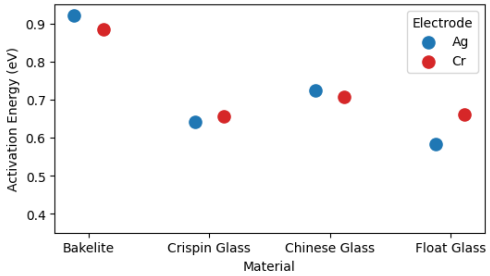
Both processes exhibit thermally activated behavior. The comparison between E_a^{σ} and E_a^{rel} allows studying whether conduction and relaxation are governed by the same microscopic mechanism.

Comparison of Activation Energies

Activation energies allow comparing the thermal behavior of the materials and evaluating the influence of the electrode type.

	E_a^{rel} [eV]	
Material	**Ag.**	**Cr.**
Bakelite	0.918(10)	0.887(11)
Crispin Glass	0.642(09)	0.656(09)
Chinese Glass	0.726(09)	0.707(15)
Float Glass	0.583(58)	0.660(43)

Fitting range: ± 25 K around 300 K.



Observations

- Bakelite presents the highest energy barrier.
- Differences between materials are greater than differences between electrodes.
- The dominant mechanism remains practically unaltered.

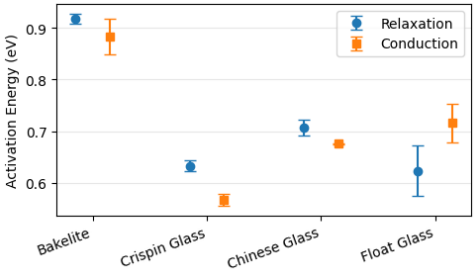
Conduction and Relaxation

Once the materials have been compared, we can address the main question of the work: are conduction and relaxation governed by the same mechanism?

Material	E_a^{rel}	E_a^{cond}	$\triangle E_a$
Bakelite	0.887	0.944	-0.057
Crispin Glass	0.633	0.567	+0.066
Chinese Glass	0.707	0.676	+0.031
Float Glass	0.623	0.716	-0.093

In all materials:

$$|\Delta E_a| < 0.1 \text{ eV}$$



Interpretation

- Very similar activation energies for the mecanism of conductivity and relaxation.
- Compatible with the same microscopic mechanism.
- Indicative of charge-carrier transport, compatible with ionic conduction.

KEY RESULT 2: Unified Transport Mechanism

Microscopic Physics

Equality of activation energies and BNN validity suggest that conduction and polarization may arise from closely related charge-carrier dynamics.

The results are compatible with a charge-carrier hopping mechanism (ex. H^+) between potential wells in the glass network:

- **Short-range restricted hops:** Produce AC polarization (ε' and τ_{CD}).
- **Long-range percolation:** Produces the DC steady-state flow (σ_{DC}).

Detector response at high rates is fundamentally governed by this bulk potential barrier.

Conclusions

1. **CD vs. RC Paradigm:** The results show that a single exponential constant ('RC model') does not fully capture the non-exponential relaxation observed in these materials.
2. **Unified Microscopic Mechanism:** The M'' modulus, BNN relation, and $E_a^{DC} \approx E_a^{AC}$ prove that bulk conduction and polarization are driven by the same microscopic mechanism.
3. **Material Optimization:** Low-resistivity glasses (Chinese and **Crispin**) show faster relaxation dynamics, which may be advantageous for high-rate RPC operation.
4. **Ongoin:** Quantitative evaluation of these results on RPC performance.

Thank You!

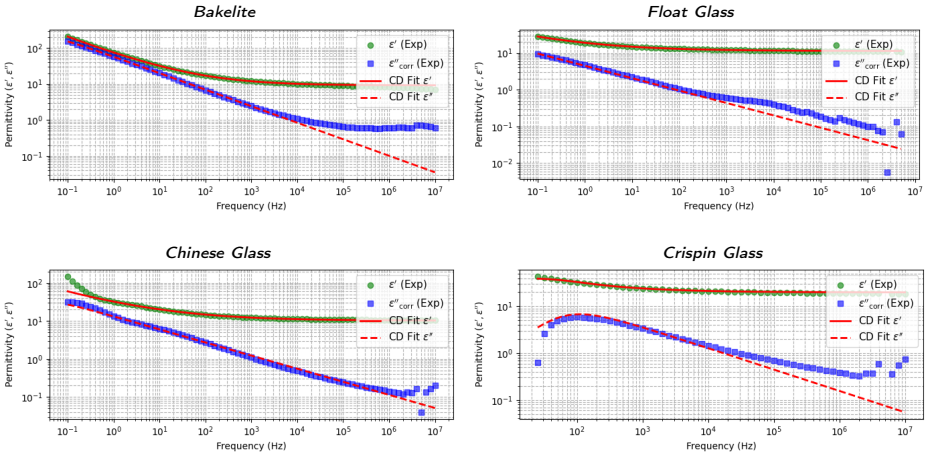
Questions & Discussion

References

- D. González-Díaz *et al.*, *Nucl. Phys. B Proc. Suppl.* **158** (2006) 111.
- C. Lippmann *et al.*, *Nucl. Phys. B Proc. Suppl.* **158** (2006) 127.
- D. González-Díaz *et al.*, *Nucl. Instrum. Meth. A* **602** (2009) 713.
- B. Bilki *et al.*, *JINST* **4** (2009) P06003.
- D. Stocco *et al.*, *J. Phys. D: Appl. Phys.* **58** (2025) 26.

Backup

Validation of the Cole-Davidson Model

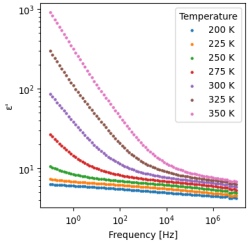


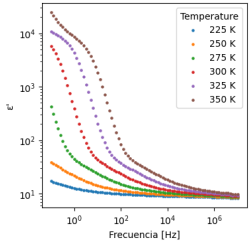
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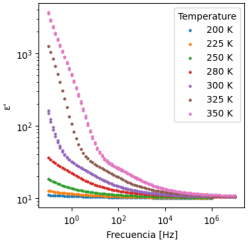
Dielectric Response: Real Permittivity

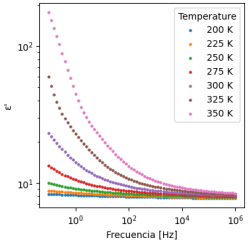
Bakelite | **Crispin Glass** | **Chinese Glass** | **Float Glass**

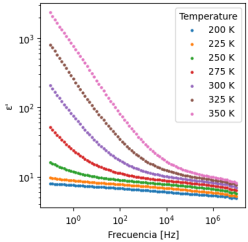
Chromium Electrode Silver Electrode

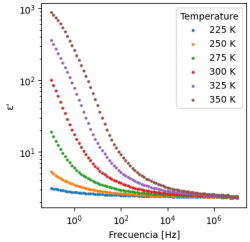


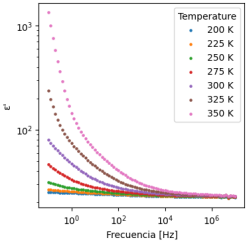


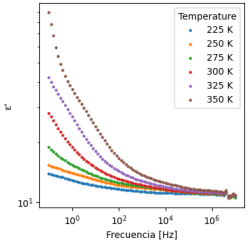








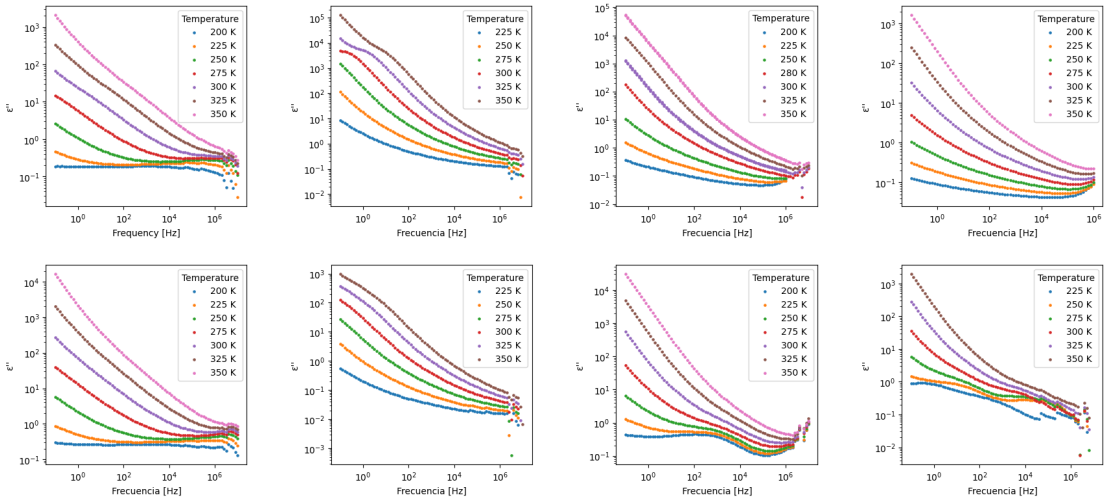




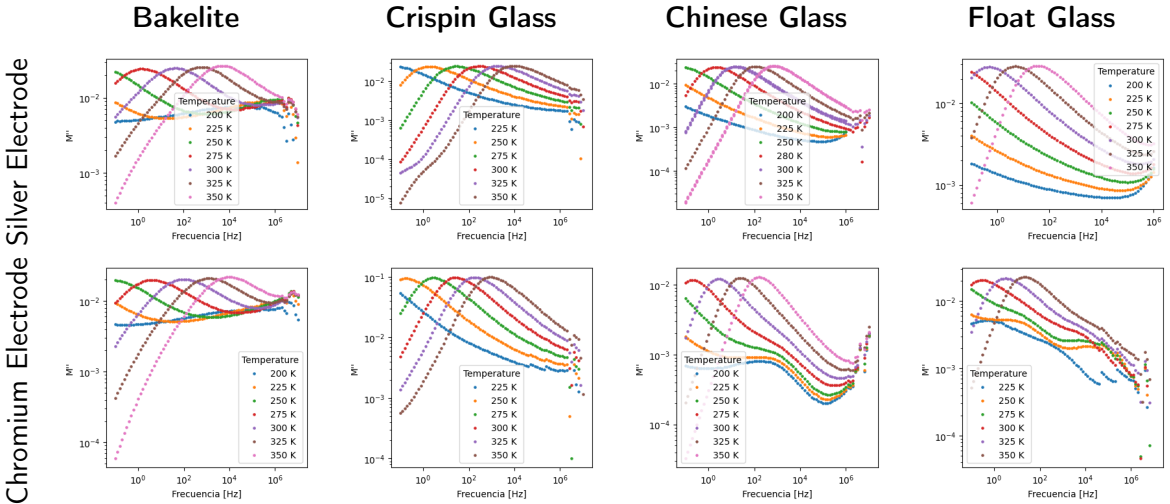
Dielectric Response: Imaginary Permittivity

Bakelite | **Crispin Glass** | **Chinese Glass** | **Float Glass**

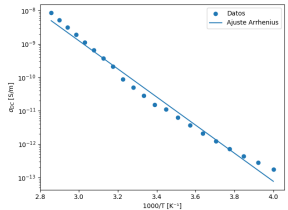
Chromium Electrode Silver Electrode

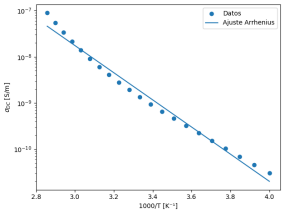


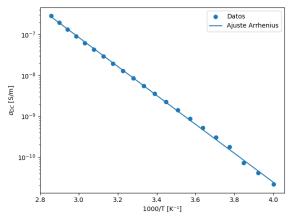
Imaginary Modulus

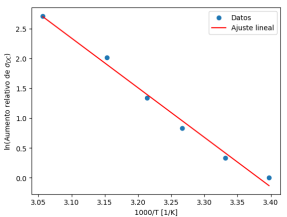


Conduction Characterization





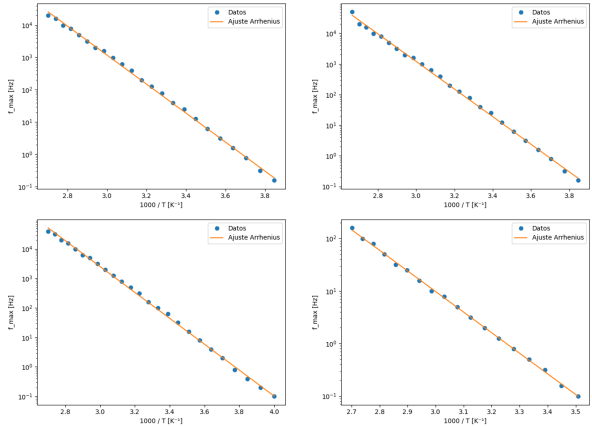




Interpretation

- Conductivity increases with temperature.
- Behavior consistent with a thermally activated process.
- Differences of up to two orders of magnitude between materials.
- The nature of the material dictates its electrical response.

Relaxation Characterization



Interpretation

- The M'' peak shifts to higher frequencies as temperature increases.
- Relaxation accelerates with temperature.
- The characteristic frequency enables direct comparison between materials.