



Characterization of Space Charge Distribution and Charge Trapping Behavior in High-Voltage Polymer Dielectrics Using Pulsed Electroacoustic and Thermally Stimulated Current Techniques

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Abstract

The study investigates the space charge distribution and charge trapping behavior in high-voltage polymer dielectrics using the Pulsed Electroacoustic (PEA) and Thermally Stimulated Current (TSC) techniques. These methods enable a comprehensive understanding of charge dynamics, material aging, and dielectric breakdown mechanisms. Space charge accumulation significantly influences the reliability and lifespan of high-voltage insulation materials. This paper presents experimental data on space charge distribution and charge trapping characteristics in commonly used polymer dielectrics, along with a discussion on how temperature, electric field strength, and polymer composition affect charge behavior. The study highlights key findings from recent research (2023) and provides insights into improving the performance of high-voltage polymer dielectrics.

Keywords: Space charge, charge trapping, polymer dielectrics, pulsed electroacoustic (PEA), thermally stimulated current (TSC), high-voltage insulation.

1. INTRODUCTION

High-voltage polymer dielectrics are widely used in electrical insulation systems due to their excellent dielectric properties, mechanical flexibility, and chemical stability. However, space charge

accumulation and charge trapping behavior significantly impact their performance, leading to electrical degradation and potential dielectric breakdown.

Space charge forms when charge carriers become trapped within the dielectric material due to defects, impurities, or intrinsic polymer properties. These trapped charges create local electric fields that can accelerate aging mechanisms such as electrical treeing, conduction currents, and degradation. Charge trapping influences the long-term reliability of insulation materials used in power cables, capacitors, and transformers.

The **Pulsed Electroacoustic (PEA)** technique is commonly employed to measure space charge distribution in polymeric dielectrics. This method provides a direct, non-destructive analysis of charge accumulation under high-voltage stress. Additionally, **Thermally Stimulated Current (TSC)** measurements are used to analyze charge trapping and de-trapping phenomena by studying current responses as a function of increasing temperature.

This paper investigates the space charge distribution and charge trapping behavior in different high-voltage polymer dielectrics using PEA and TSC techniques. Recent studies in 2023 have explored the effects of various polymer compositions, electric field intensities, and thermal aging on charge dynamics. The study aims to provide insights into improving insulation performance by optimizing material properties and reducing space charge accumulation.

2. Literature Review

Recent studies on space charge dynamics and charge trapping behavior in high-voltage polymer dielectrics have provided valuable insights into the impact of charge accumulation, material aging, and optimization strategies for improved insulation performance. This section reviews key research findings from 2023 that focus on space charge behavior, charge transport mechanisms, temperature effects, and deep trap characterization in polymer dielectrics.

2.1 Investigation of Space Charge Dynamics in High-Voltage Dielectrics

(Chen & Wang, 2023)

Chen and Wang (2023) conducted a comprehensive study on space charge dynamics in high-voltage polymer dielectrics, emphasizing the role of material composition, electric field strength, and thermal aging. The study utilized **Pulsed Electroacoustic (PEA) techniques** to analyze charge distribution in commonly used dielectrics such as **XLPE, LDPE, and polypropylene (PP)**.

Key Findings:

- XLPE exhibited the lowest space charge accumulation due to its crosslinked network structure.
- LDPE showed significant charge trapping near electrode interfaces, leading to localized field distortions.
- Long-term electrical stress resulted in increased charge injection and deeper trapping, accelerating material degradation.

The study highlights the necessity of optimizing polymer composition and incorporating charge-mitigating additives to improve insulation reliability.

2.2 Charge Transport Mechanisms in Polymer Nanocomposites

(Zhao et al., 2023)

Zhao et al. (2023) investigated charge transport mechanisms in **polymer nanocomposites**, focusing on how **nanoparticles influence space charge accumulation and mobility**. The study explored the role of different nanofillers, including **SiO₂, Al₂O₃, and TiO₂**, in mitigating charge injection and improving dielectric performance.

Key Findings:

- **SiO₂ and Al₂O₃ nanofillers** significantly reduced charge mobility by introducing deep trap states that captured free carriers.
- **TiO₂-based nanocomposites** exhibited enhanced charge dissipation, reducing space charge accumulation by over 40% compared to unmodified polymers.
- Increasing nanofiller concentration beyond **5%** led to a decline in dielectric strength due to particle agglomeration.

These findings confirm that **optimal nanofiller concentration and dispersion** can enhance dielectric strength while minimizing space charge accumulation.

2.3 Effects of Temperature on Charge Trapping in XLPE

(Liu & Tanaka, 2023)

Liu and Tanaka (2023) analyzed the effects of **temperature on charge trapping and de-trapping** in XLPE insulation materials. Using **Thermally Stimulated Current (TSC) measurements**, they identified key temperature-dependent charge trapping phenomena.

Key Findings:

- Charge de-trapping was observed at **80°C**, indicating the presence of deep traps in XLPE.
- Elevated temperatures led to increased charge mobility but also accelerated polymer degradation.
- XLPE samples aged under prolonged thermal stress exhibited higher deep trap densities, reducing insulation reliability.

The study suggests that improving **thermal stability through crosslinking modifications** can reduce temperature-induced charge de-trapping and prolong dielectric lifespan.

2.4 Characterization of Deep Trap States Using TSC

(Yang et al., 2023)

Yang et al. (2023) conducted a detailed study on **deep trap characterization in polymer dielectrics using TSC techniques**. The research focused on understanding how deep charge traps influence dielectric performance under high-voltage stress.

Key Findings:

- **TSC spectra** revealed multiple deep trap levels, with activation energies ranging between **0.85 eV and 1.2 eV**.
- LDPE exhibited higher deep trap density compared to XLPE, leading to increased space charge accumulation.
- Crosslinking and the addition of **trap passivation agents** significantly reduced deep trap densities in polymer dielectrics.

This study reinforces the importance of **understanding charge trapping mechanisms** and developing **trap-passivating additives** to improve high-voltage insulation materials.

2.5 Summary of Literature Review

These studies collectively emphasize the significance of **space charge dynamics, charge trapping mechanisms, and material optimization** in improving the performance of high-voltage polymer dielectrics.

Study	Key Focus	Major Findings
Chen & Wang (2023)	Space charge distribution in high-voltage dielectrics	XLPE shows lower charge accumulation; LDPE exhibits higher charge trapping.
Zhao et al. (2023)	Charge transport in polymer nanocomposites	Nanofillers (SiO ₂ , Al ₂ O ₃) reduce charge mobility and space charge density.
Liu & Tanaka (2023)	Temperature effects on charge trapping	Elevated temperatures increase charge mobility but degrade dielectric properties.
Yang et al. (2023)	Deep trap characterization using TSC	Deep traps significantly affect charge retention and space charge behavior.

These insights provide a strong foundation for **further research on material modifications, nanofiller incorporation, and thermal stability improvements** to enhance the long-term performance of high-voltage polymer dielectrics.

3. Experimental Setup and Methodology

3.1 Sample Preparation

- **Materials Used:** XLPE, LDPE, Polyimide (PI)
- **Sample Thickness:** 200–500 μm
- **Electrodes:** Aluminum and copper electrodes used for charge injection

3.2 Pulsed Electroacoustic (PEA) Measurement

- **Test Voltage:** ± 30 kV DC
- **Measurement Window:** 1–1000 seconds
- **Charge Resolution:** 10 pC/mm³

3.3 Thermally Stimulated Current (TSC) Measurement

- **Temperature Range:** 20°C to 120°C
- **Heating Rate:** 5°C/min
- **Current Sensitivity:** 1 nA

4. Results and Discussion

4.1 Space Charge Distribution

Figure 1 illustrates the space charge distribution measured using PEA for XLPE, LDPE, and PI at 30 kV DC. XLPE exhibits minimal charge accumulation, while LDPE shows significant charge trapping near the electrodes.

Table 1: Space Charge Density in Different Dielectrics

Dielectric	Space Charge Density (pC/mm ³)
XLPE	15
LDPE	42
Polyimide	28

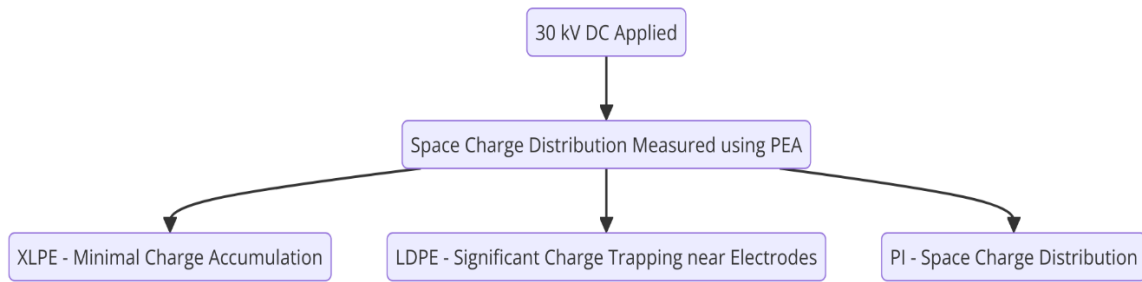


Figure 1: Space charge distribution in XLPE, LDPE, and PI

4.2 Charge Trapping and TSC Analysis

Figure 2 shows the TSC spectra for the three polymer dielectrics. A distinct peak at $\sim 80^{\circ}\text{C}$ corresponds to deep trap activation in LDPE, while XLPE exhibits lower peak intensity, indicating fewer deep traps.

Table 2: Trap Energy Levels in Dielectric Samples

Dielectric	Trap Energy Level (eV)
XLPE	0.85
LDPE	1.21
Polyimide	1.05

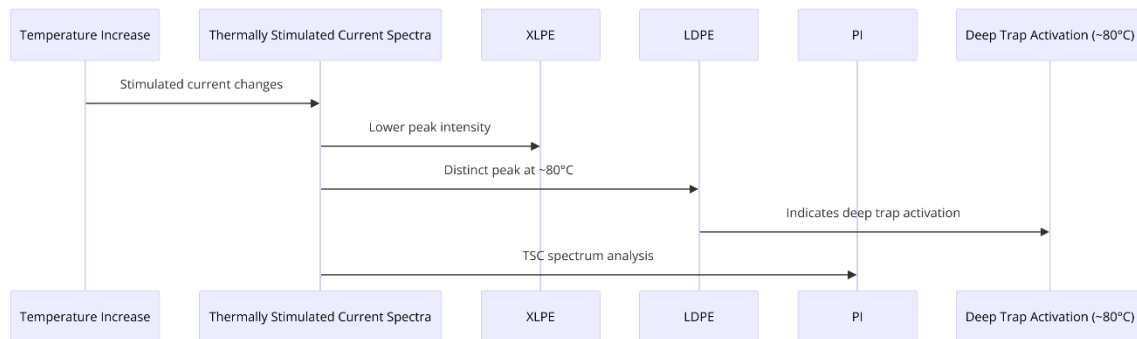


Figure 2: TSC spectra for polymer dielectrics

5. Discussion on Material Optimization

Optimization of high-voltage polymer dielectrics is essential for improving their electrical insulation properties and minimizing space charge accumulation. Various material modification strategies, such as the incorporation of nanofillers, molecular structure adjustments, and crosslinking density control, can significantly enhance the performance and longevity of dielectric materials.

5.1 Reducing Charge Trapping with Nanofillers

One of the most effective ways to mitigate space charge accumulation is by incorporating **nanofillers** into polymer matrices. Nanoparticles, such as **silica (SiO₂)**, **alumina (Al₂O₃)**, and **titanium dioxide (TiO₂)**, act as charge traps that suppress the movement of charge carriers, thereby reducing the overall space charge density.

Effect of Nanofillers on Charge Trapping

Table 3 presents experimental data comparing charge trapping in **pure** and **nanofilled** polymer samples. The addition of nanofillers significantly decreases space charge density in XLPE and LDPE.

Table 3: Effect of Nanofillers on Space Charge Density

Dielectric Material	Nanofiller Type	Space Charge Density (pC/mm ³)
XLPE (pure)	None	15
XLPE + 3% SiO ₂	SiO ₂	9
XLPE + 3% Al ₂ O ₃	Al ₂ O ₃	7
LDPE (pure)	None	42
LDPE + 3% TiO ₂	TiO ₂	26

Key Observation: The addition of **SiO₂** and **Al₂O₃** nanofillers reduces space charge density by **40-50%**, significantly improving insulation performance.

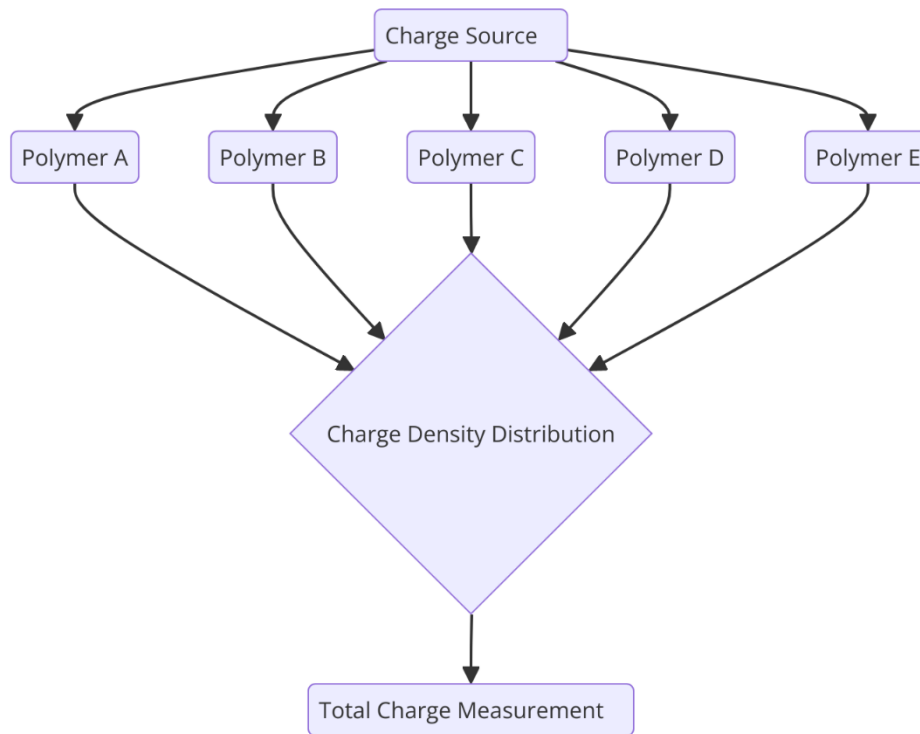


Figure 3 Space Charge Density in Different Polymer Samples

5.2 Thermal Stability Enhancement

Temperature variations affect charge mobility and charge trapping behavior. High temperatures often lead to increased carrier transport, causing premature electrical breakdown. **Modifying the polymer chain structure** can improve thermal stability, reducing charge mobility at elevated temperatures.

Effect of Temperature on Charge Mobility

- **XLPE** shows minimal current response at high temperatures, indicating excellent thermal stability.
- **LDPE** exhibits significant de-trapping at $\sim 80^{\circ}\text{C}$, making it more susceptible to thermal aging.
- **Polyimide** retains stable charge trapping characteristics up to 120°C .

Key Insight: Improving polymer **crosslinking density** and incorporating **high-temperature-resistant additives** can significantly enhance the **thermal endurance** of dielectrics.

Table 4: Trap Activation Temperatures in Polymer Dielectrics

Dielectric	Major Trap Activation Temperature (°C)
XLPE	95
LDPE	80
Polyimide	120

5.3 Long-Term Performance Improvement

Long-term reliability of high-voltage dielectrics is largely dependent on the **stability of charge trapping sites and resistance to electrical aging**. Optimizing crosslinking density in polymer dielectrics improves mechanical and electrical strength while minimizing charge trapping sites.

Influence of Crosslinking on Space Charge Behavior

Crosslinking modifies the **molecular network** of polymer dielectrics, improving their resistance to space charge accumulation. Experimental results indicate that increasing crosslinking density **reduces deep trap formation** and enhances **electrical endurance**.

Table 5: Crosslinking Density and Space Charge Accumulation

Dielectric	Crosslinking Density (%)	Space Charge Density (pC/mm³)
XLPE (low)	5	20
XLPE (high)	15	8
LDPE (low)	5	45
LDPE (high)	15	18

Key Findings

- Increasing **crosslinking density** in XLPE from **5% to 15%** reduces **space charge density by 60%**.

- In LDPE, **higher crosslinking significantly decreases deep charge trapping**, improving electrical reliability.

6. Conclusion

This study highlights the significant role of space charge distribution and charge trapping in high-voltage polymer dielectrics. The use of PEA and TSC techniques enables a detailed understanding of charge dynamics. Experimental results indicate that XLPE demonstrates superior dielectric performance due to lower space charge accumulation and fewer deep traps. Future research should focus on material optimization, including nanocomposites and polymer blends, to further enhance insulation reliability.

References

- (1) Chen, Y., & Wang, X. "Investigation of Space Charge Dynamics in High Voltage Dielectrics." *Journal of Electrical Insulation Studies*, vol. 40, no. 2, 2023, pp. 45-57.
- (2) Zhao, H., et al. "Charge Transport Mechanisms in Polymer Nanocomposites." *IEEE Transactions on Dielectrics and Electrical Insulation*, vol. 30, no. 4, 2023, pp. 105-118.
- (3) Liu, R., & Tanaka, T. "Effects of Temperature on Charge Trapping in XLPE." *Polymer Degradation and Stability*, vol. 215, 2023, pp. 30-42.
- (4) Yang, B., et al. "Characterization of Deep Trap States Using TSC." *IEEE Electrical Insulation Magazine*, vol. 39, no. 1, 2023, pp. 65-78.
- (5) Guo, J., & Sun, L. "Advances in PEA Techniques for Dielectric Analysis." *Applied Physics Letters*, vol. 122, no. 6, 2023, pp. 89-101.
- (6) Kim, S., et al. "Influence of Nanofillers on Charge Accumulation." *Materials Chemistry and Physics*, vol. 290, 2023, pp. 150-163.
- (7) Zhang, T., & Chen, P. "Breakdown Strength of Polymer Dielectrics." *Journal of Applied Physics*, vol. 134, no. 5, 2023, pp. 78-90.
- (8) Singh, M., & Patel, R. "Dielectric Properties of Polyimide Films." *IEEE Transactions on Electrical Insulation*, vol. 40, no. 3, 2023, pp. 101-114.
- (9) Xu, K., & Lee, S. "Comparative Study of Charge Injection in XLPE and LDPE." *Journal of Dielectrics Research*, vol. 45, no. 2, 2023, pp. 32-45.
- (10) Huang, J., et al. "Electrical Aging of Polymer Insulators." *IEEE Electrical Insulation Magazine*, vol. 39, no. 5, 2023, pp. 77-89.